Remember : it all started with island universes...

Thomas Wright's view of the Universe (XIX^{th} c.)

Interstellar Gas and Star Creation

By

SIDNEY VAN DEN BERGH

(Eingegangen am 29. Juni 1957)

*If no external supply is available, the gaz in the solar vicinity will be exhauted about **700 million years** from now*

SFR(MW) ~ 7,5 $M_\odot yr^{-1}$

(Diehl *et al*. 2006 Nature)

Molecular gas (H_2): 10^9 $M_\odot$

Neutral gas (HI): $5x10^9$ $M_\odot$

→ **Gas refilled (e.g. infall, return gas fraction) = Van den Bergh (1957)**

→ **SFR reduced with reduced gas content: SFR ~ ρ_{gas} = Schmidt (1959)**

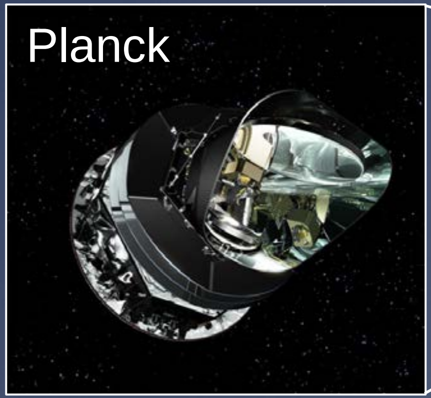
Lessons on the origin of extragalactic emission with Herschel & Planck

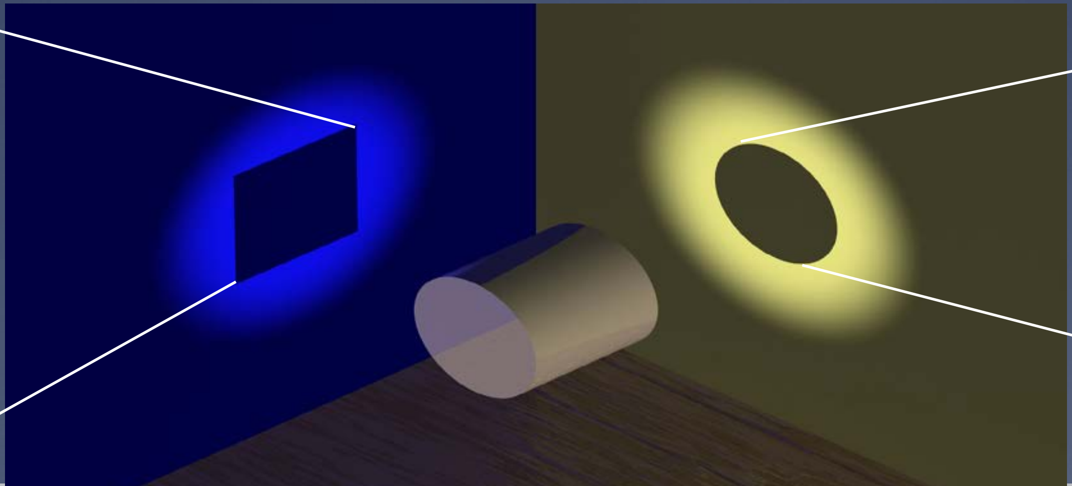
David Elbaz (CEA Saclay)

cosmology → galaxy seeds + cosmic expansion rate
→ halo mass function + infall of DM + baryons
→ fueling of galaxy growth
→ consistent with observed galaxy growth ?

- Cosmic IR background = global energetic budget of star-formation:
  how and when did the Universe spend its nucleosynthetic money ?

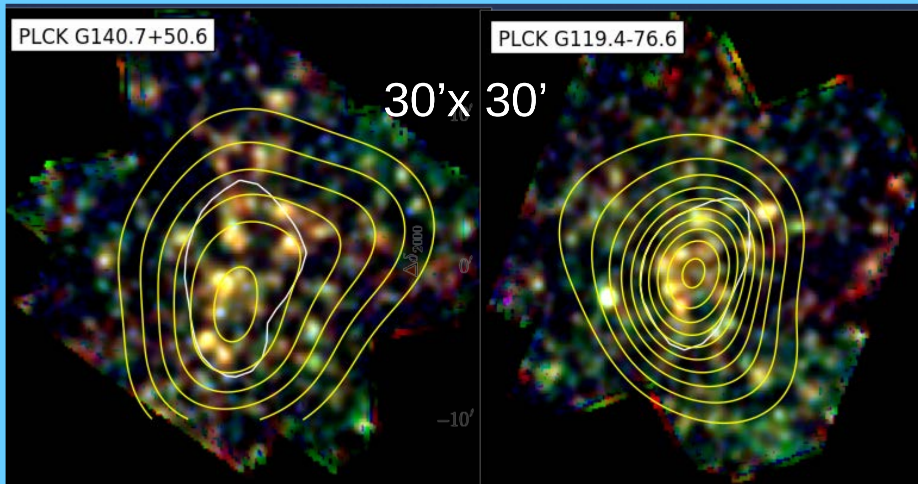
- what are the main drivers of the growth of galaxies ?
  are the key drivers in situ (internal physics) or ex situ (mergers,....) ?





Planck's view of extragalactic emission

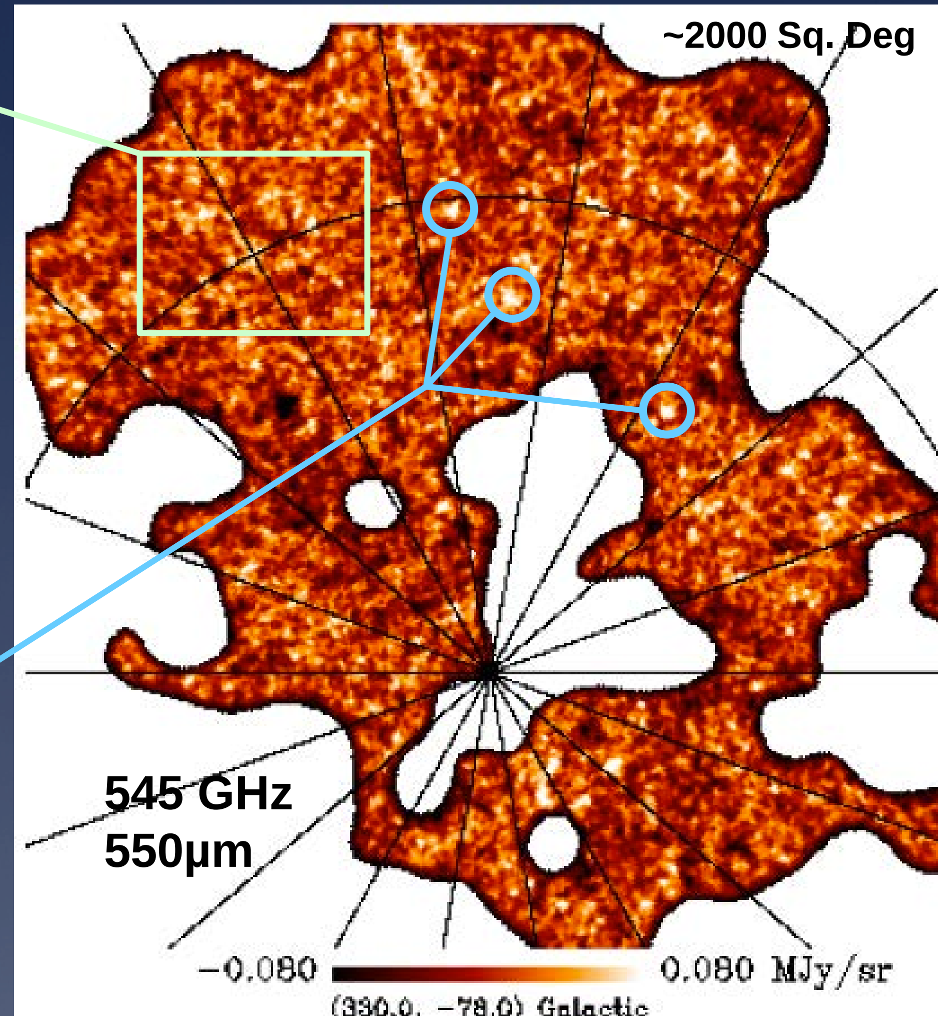
Anisotropies of CIRB



Planck (contours) / Herschel (color images)

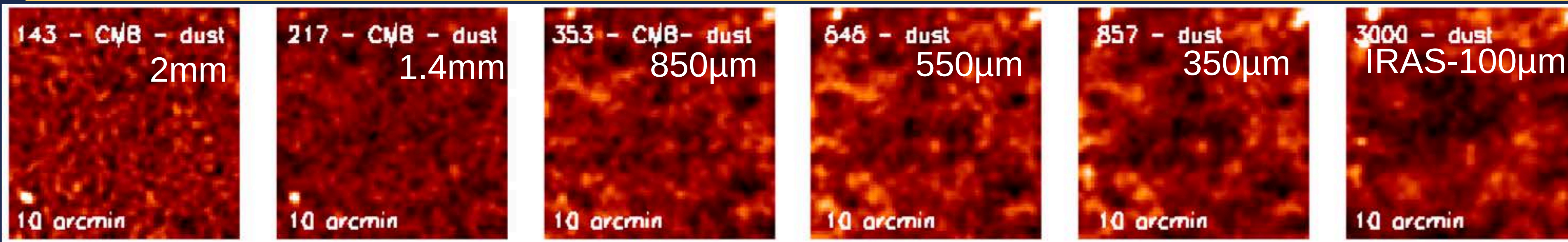
H. Dole & Planck collab PIP XXVII submitted

See L.Montier's talk & D.Guéry's poster



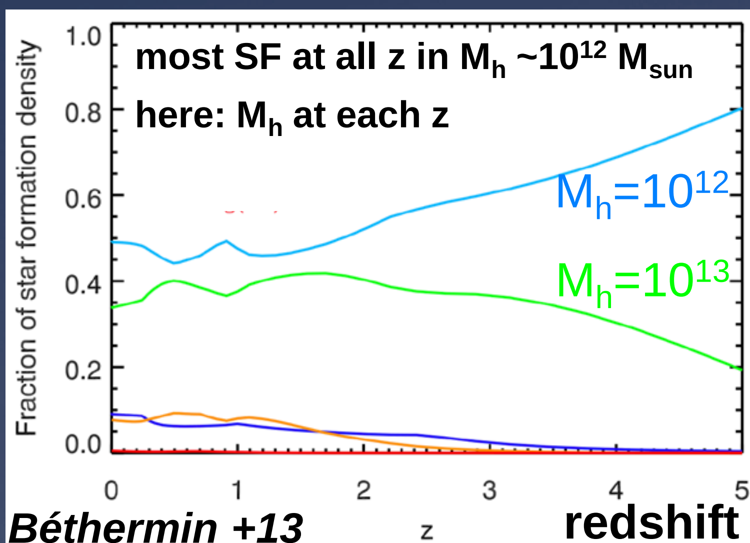
- Rare bright lensed sources ?
  - unaffected by blending → see L.Montier talk
- Blended groups of sources
  - candidate distant proto-clusters ? LSS alignments ?

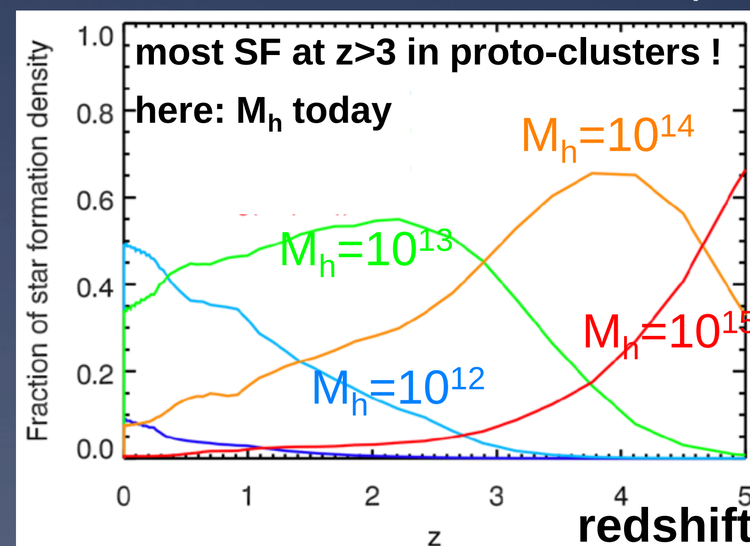
Anisotropies of the CIRB



Now auto-frequency power spectra at the wavelengths in common between Herschel and Planck are fully consistent (350 & 500 µm) [Viero +13]

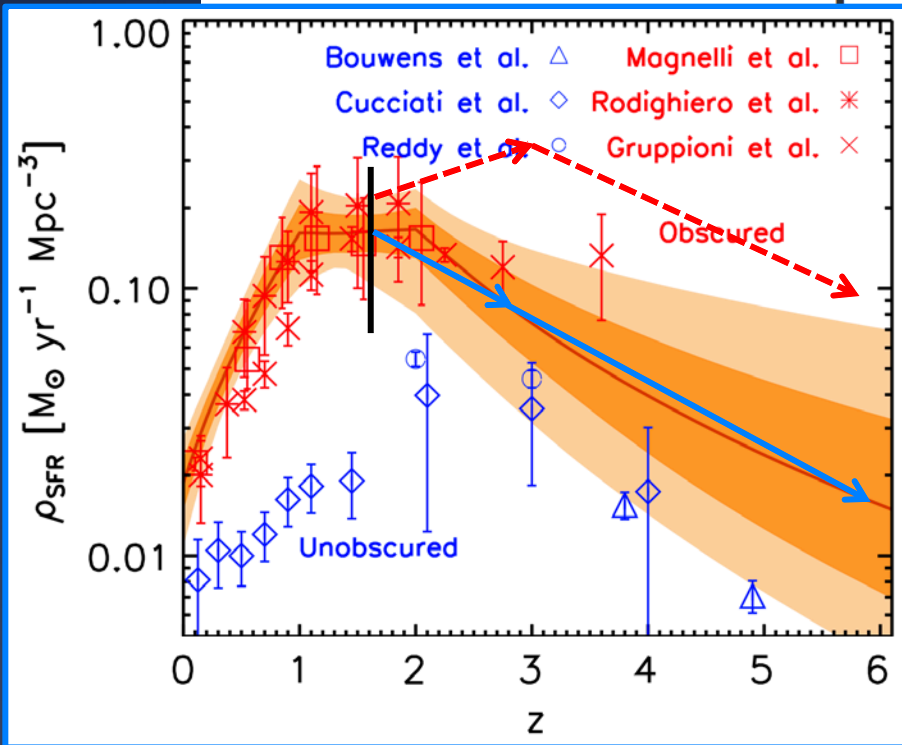
Modelling : halo mass function + IR emissivity for halo mass
→ Markov Chain MC to fit anisotropies (Planck XVIII, XXX, Herschel Viero +13)

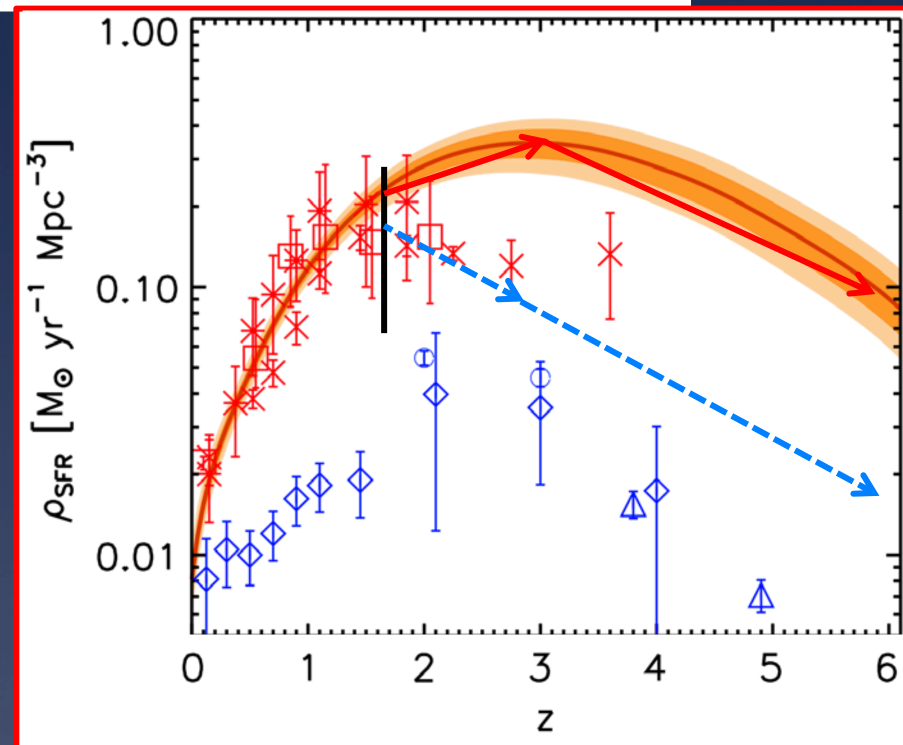


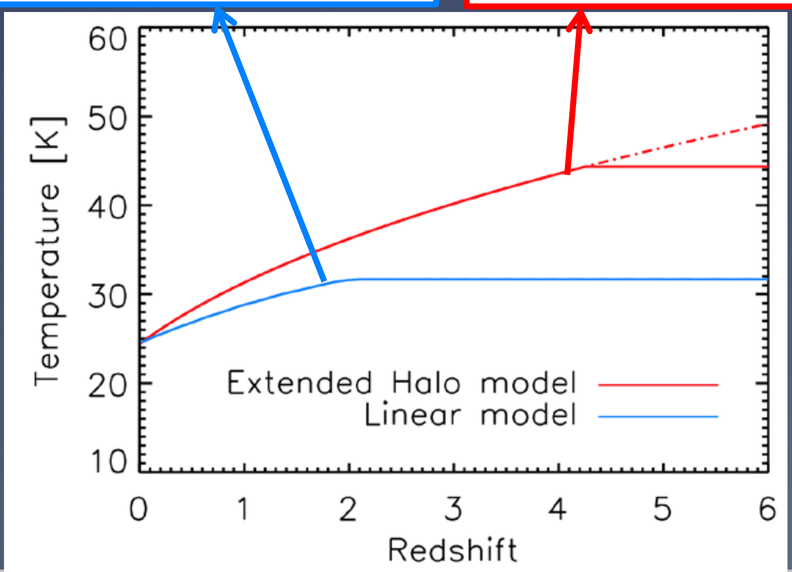


Halo mass function + M^*/M_{halo} (from abundance matching, e.g. Behroozi +13) → M* function + SFR – M* relation → SFR distribution + Herschel IR SEDs (stacking) → IR emissivity/DM

Planck 2013 results. XXX. Cosmic infrared background measurements and implications for star formation

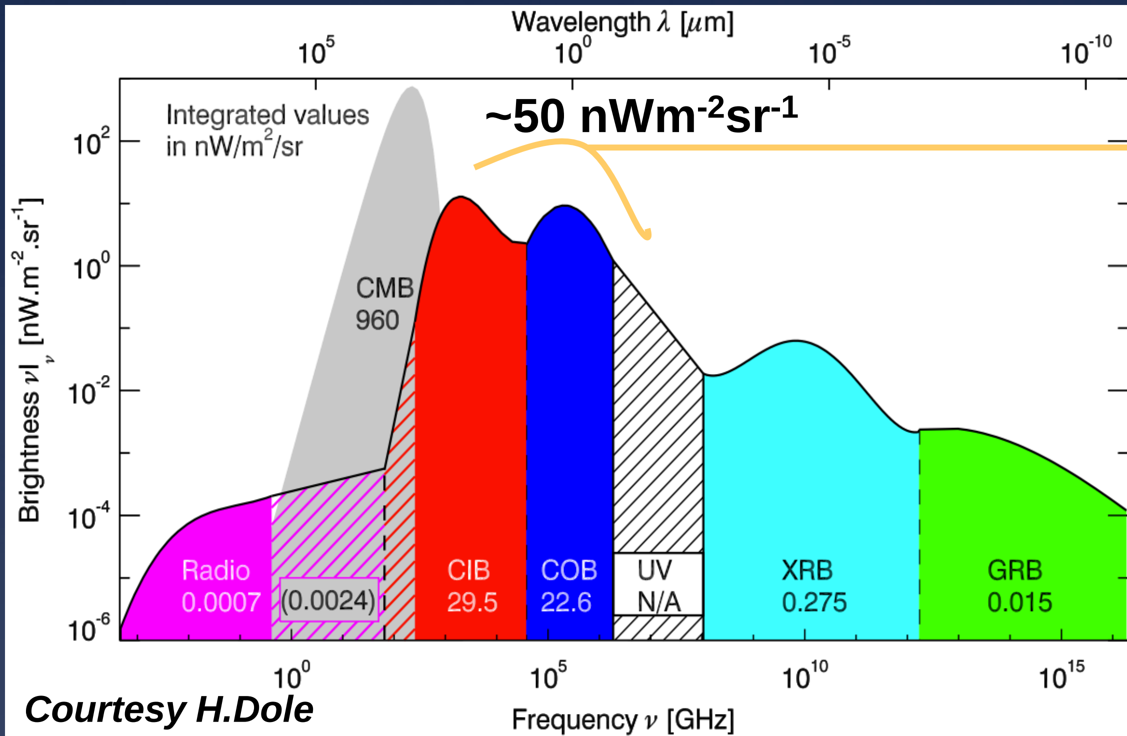


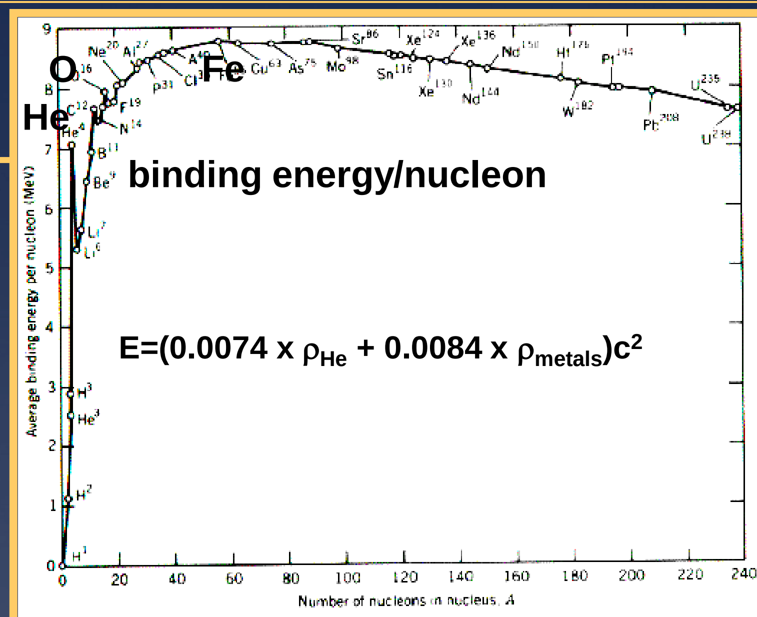




Corresponding author:
G. Lagache

Extragalactic background light ~ 5% of CMB





nucleosynthesis: EBL= $[0.0074 \times \rho_{He} + 0.0084 \times \rho_{metals}] \times c^3 / (4\pi \times (1+z))$ [W m^{-2} sr^{-1}]

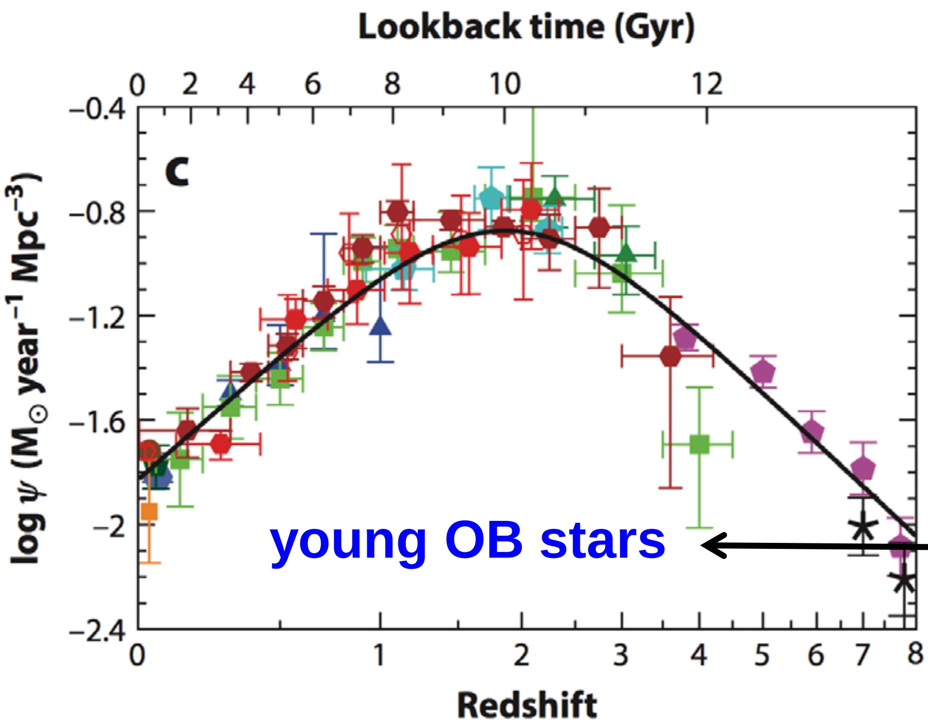
$\rho_{metals} \sim 1.5 \times 10^{-30}$ kg m^{-3} (galaxies + IGM), Sun – primordial He =0.04=2Z => $\rho_{He} \sim 5 \times 10^{-30}$ kg m^{-3}

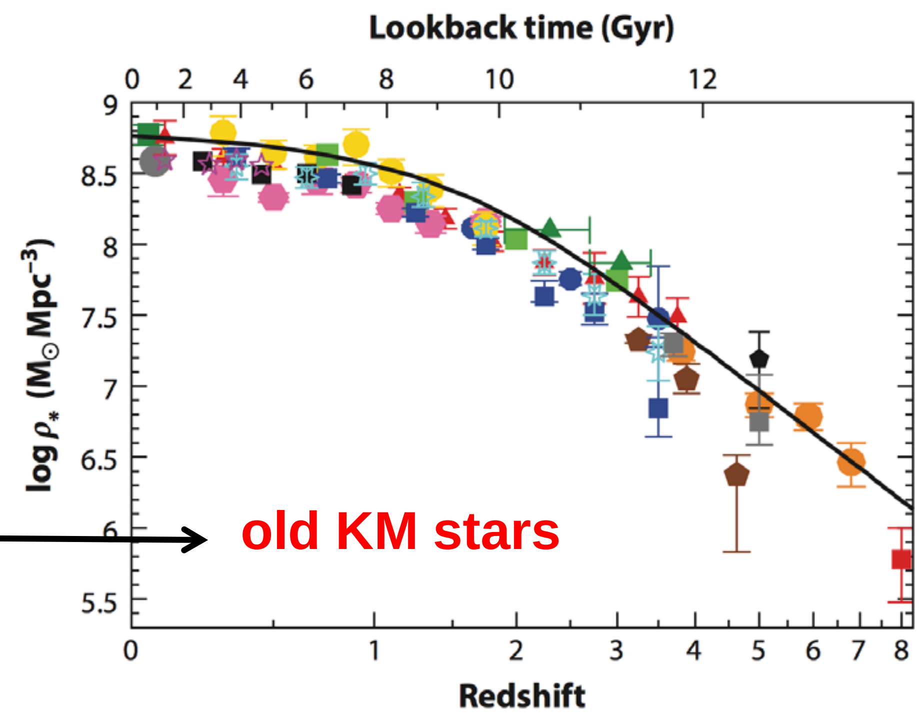
→ EBL(nucleosynthesis) ~ 140 / (1+z) [W m^{-2} sr^{-1}]

accretion: $EBL_{SMBH} = \eta \times \rho_{BH}\, c^3 / (4\pi \times (1+z))$ with $\rho_{BH} \sim 4.6 \times 10^{-32}$ kg m^{-3} (Marconi & Hunt 08)

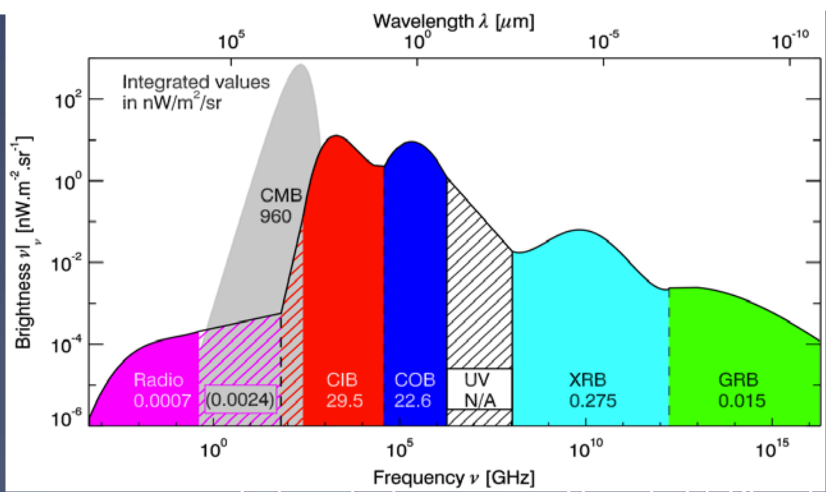
→ $IGL_{SMBH} \sim 9 / (1+z)$ nW m^{-2} sr^{-1}

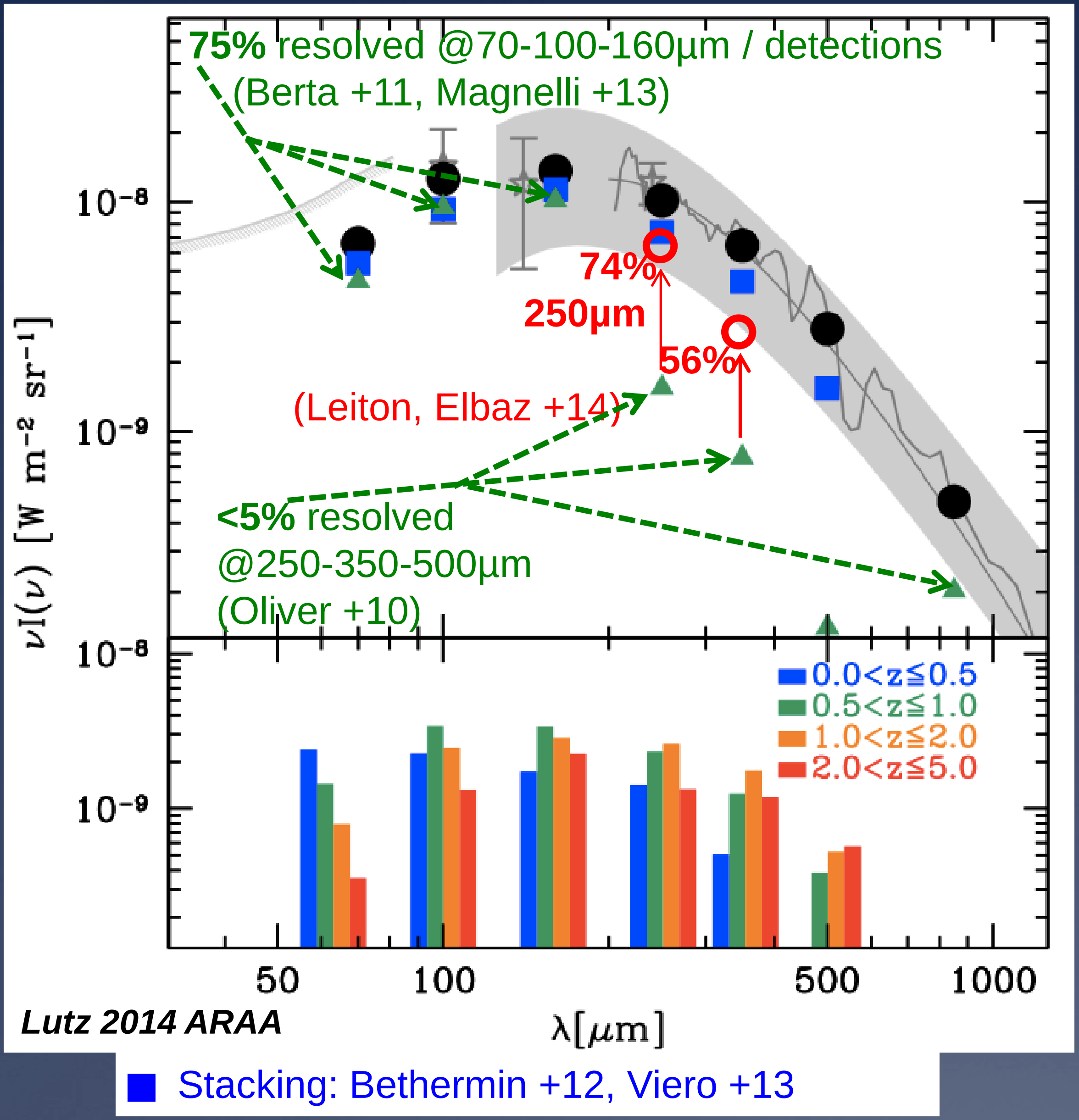
The global budget of star-formation is known

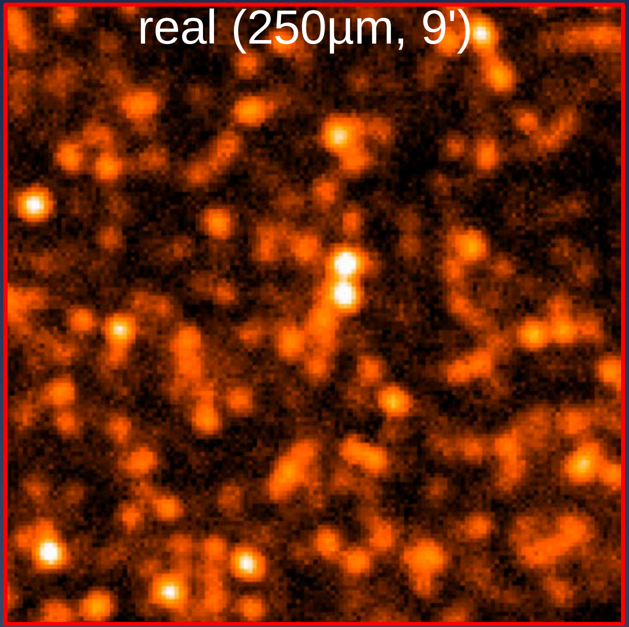


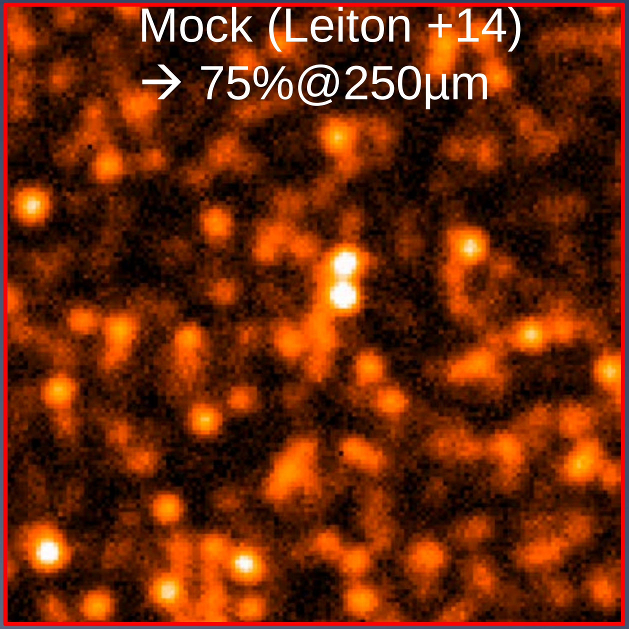


Madau & Dickinson 2014



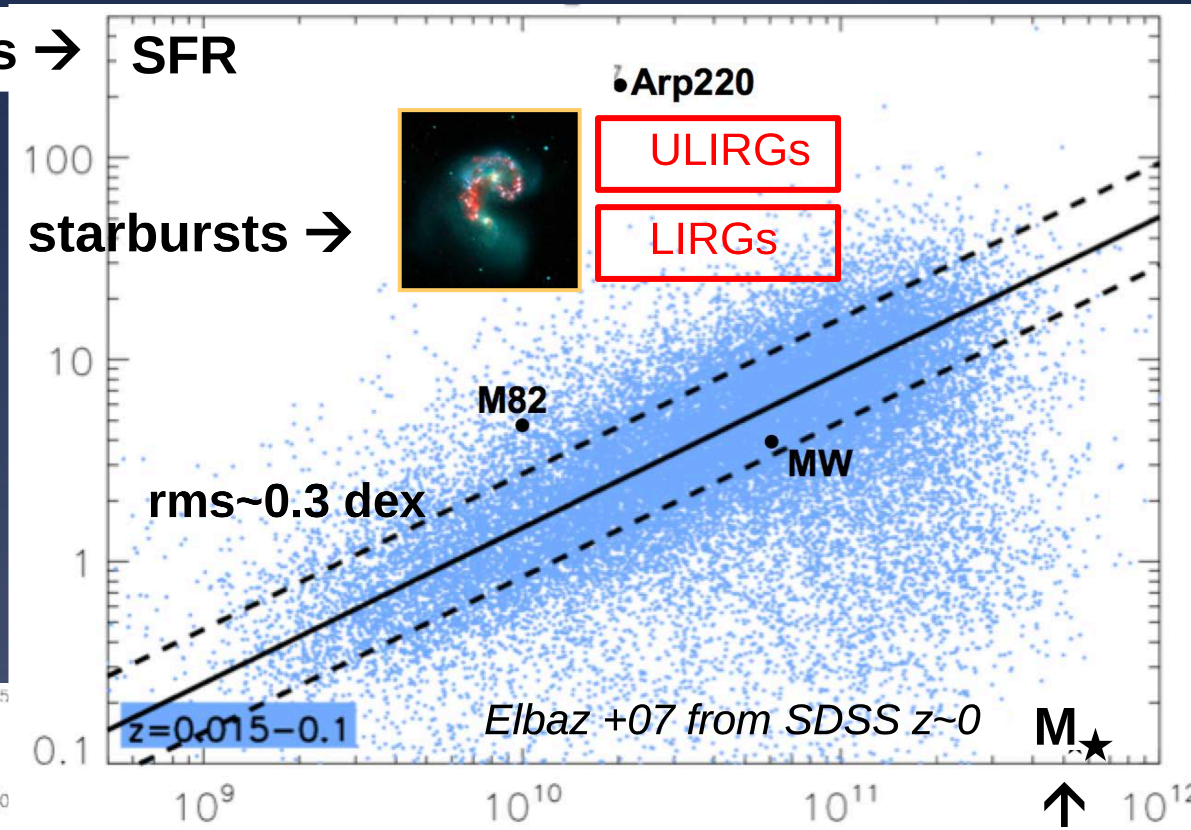

75% resolved @70-100-160µm / detections
(Berta +11, Magnelli +13)
74%
250µm
56%
(Leiton, Elbaz +14)
<5% resolved
@250-350-500µm
(Oliver +10)
νI(ν) [W m⁻² sr⁻¹]
10⁻⁸
10⁻⁹
0.0<z≦0.5
0.5<z≦1.0
1.0<z≦2.0
2.0<z≦5.0
50
100
500
1000
λ[µm]
Lutz 2014 ARAA
Stacking: Bethermin +12, Viero +13


real (250µm, 9')

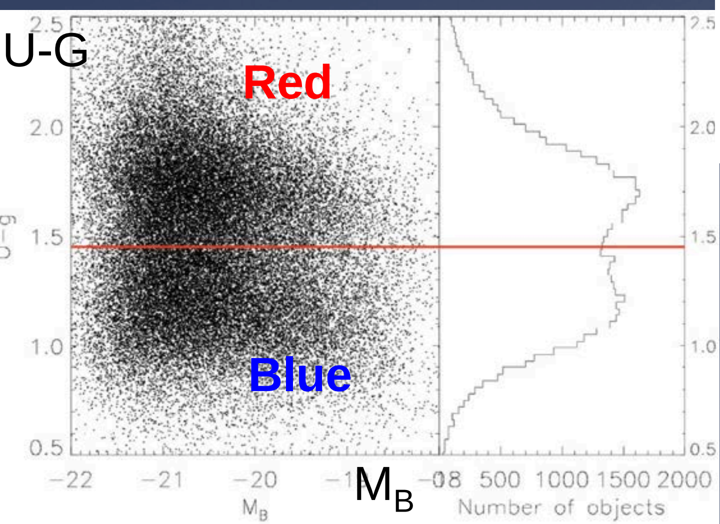

Mock (Leiton +14)
→ 75%@250µm

The main sequence of star forming galaxies

young OB stars → SFR



↑ old KM stars

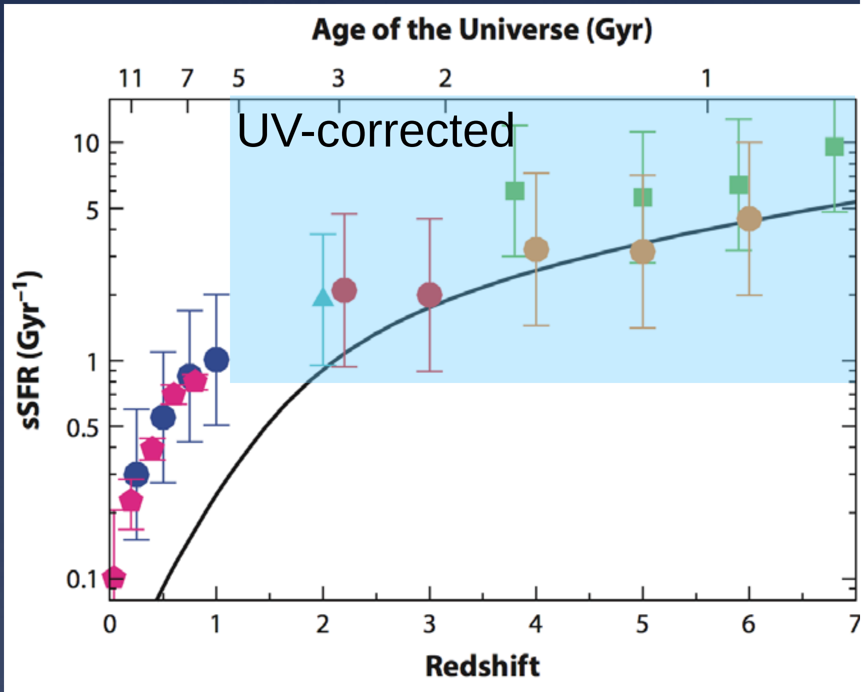


Bigger is bigger …

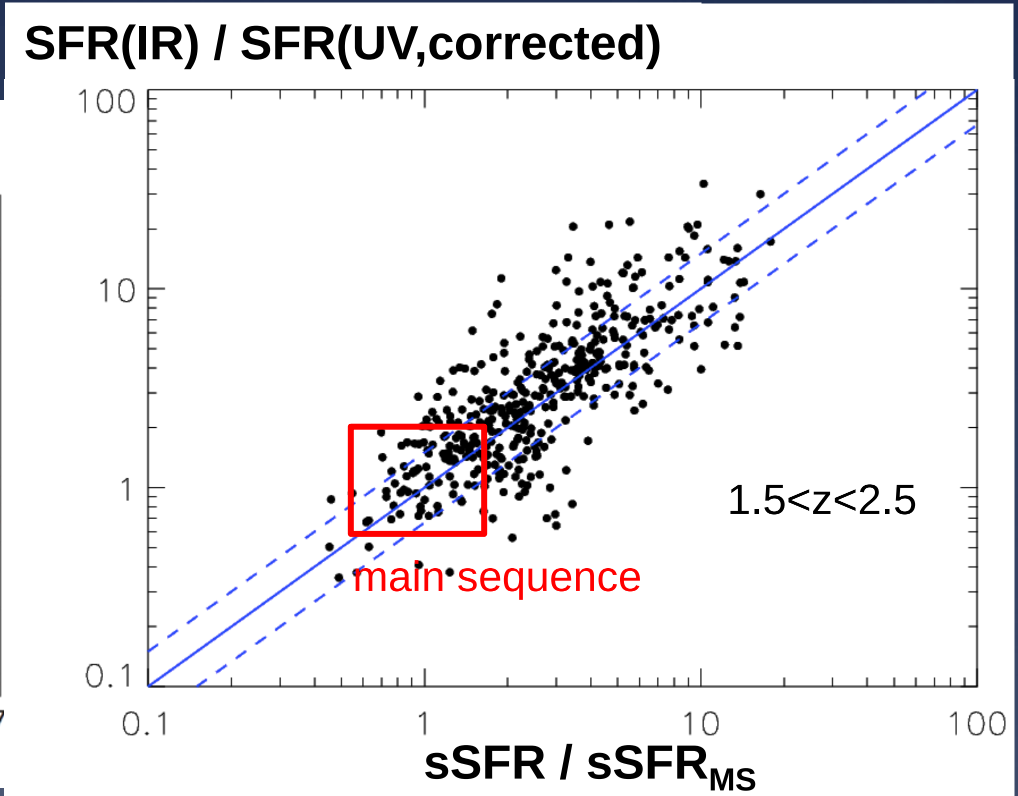
… but x2 dispersion only…

SF primarily driven by in situ processes ?

The UV view of star formation washes out the "personality" of galaxies



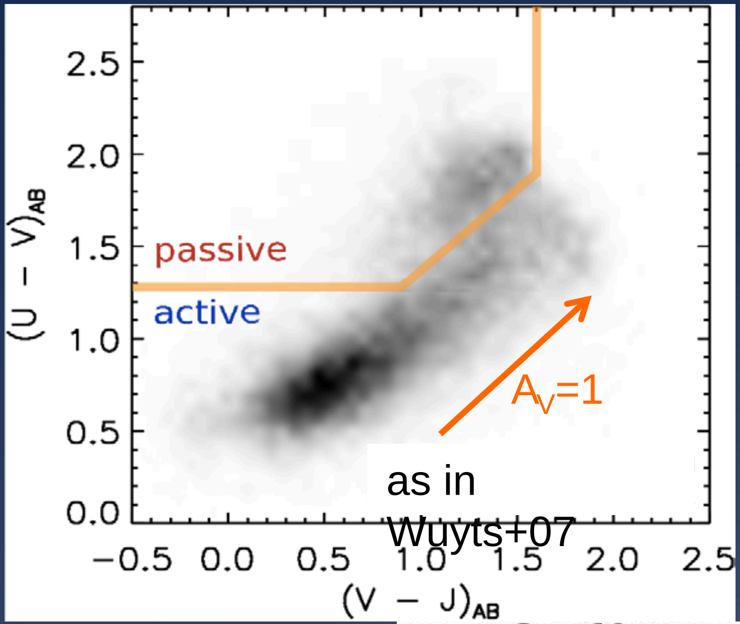
Compilation from Madau & Dickinson 2014



SFR_{IR} = SFR_{UV} x starburstiness

starburstiness= ($sSFR/sSFR_{MS}$)

Mass – selected sample in CANDELS fields (6000 galaxies)

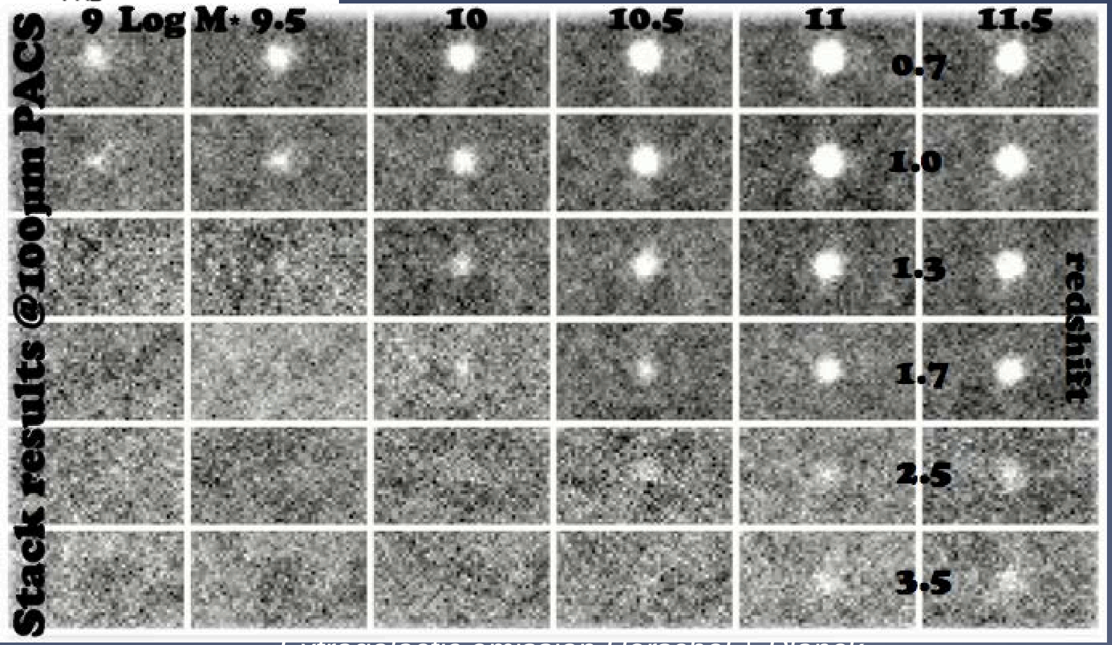


HST-WFC3 H-band selected galaxies (H<27)

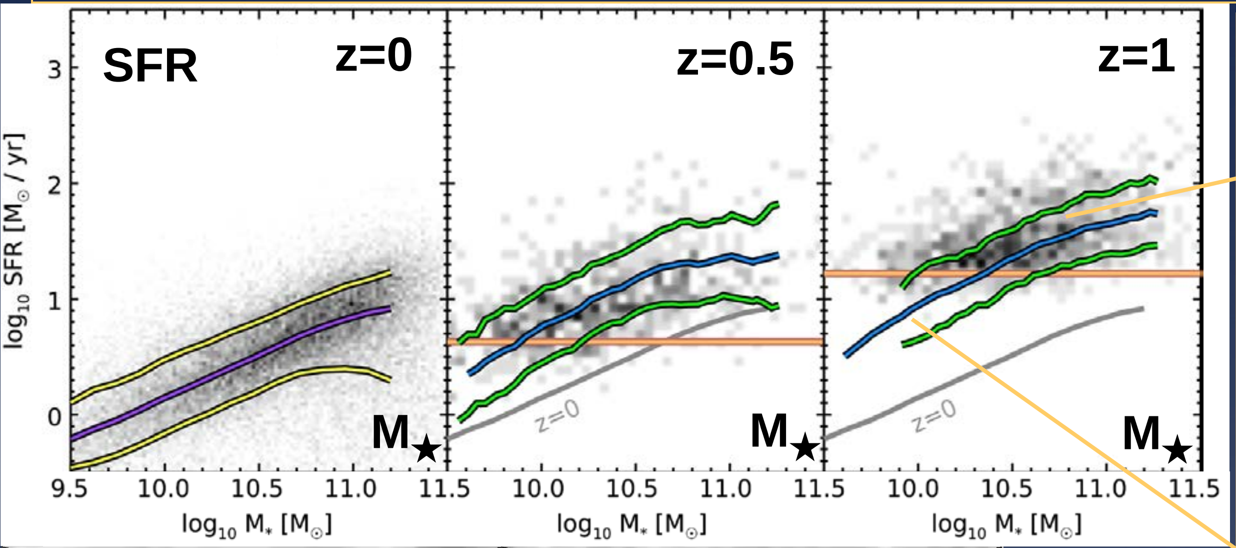
zphots $\Delta z/(1+z)\sim 2.5\%$
(code EAZY, Brammer +08)

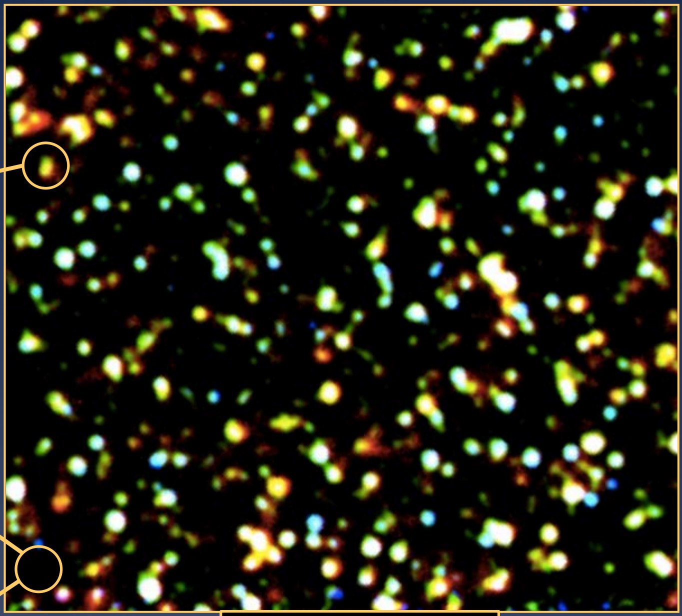
Stellar masses
(code FAST, Kriek +09)

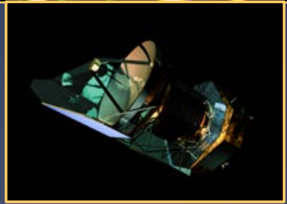
- Bruzual & Charlot (2003) stellar population
- Calzetti et al. (2000) reddening law
- delayed exponentially declining star formation history : SFR~t exp(-t/τ)

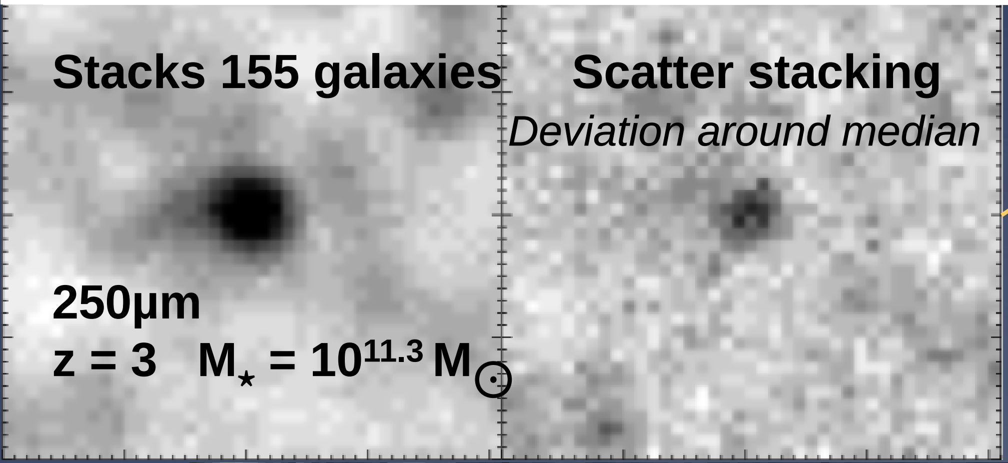


SFR – $M_\star$: the *Herschel* view on the main sequence

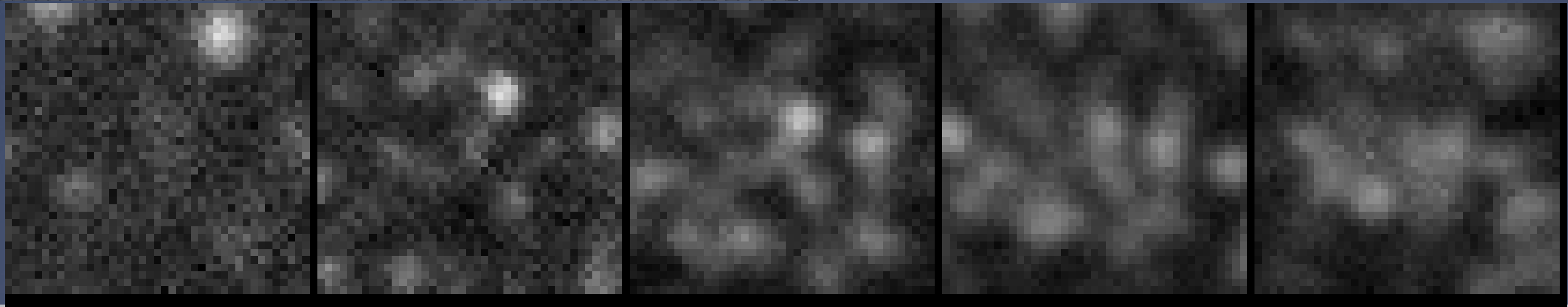




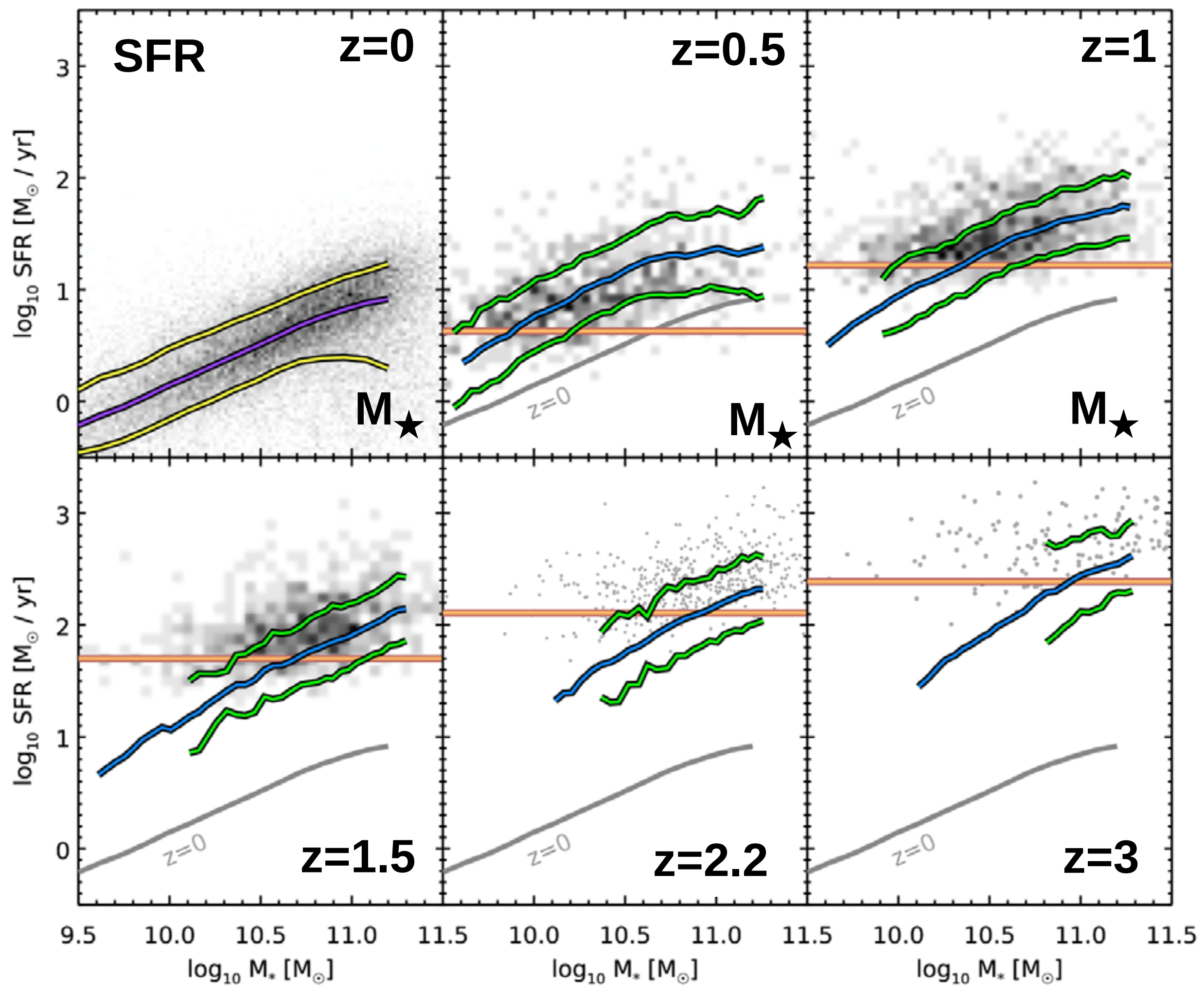


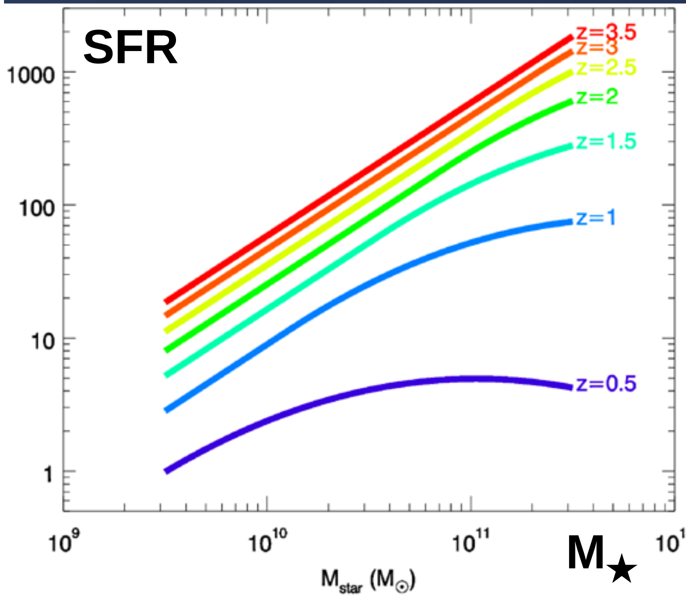


Schreiber +2014

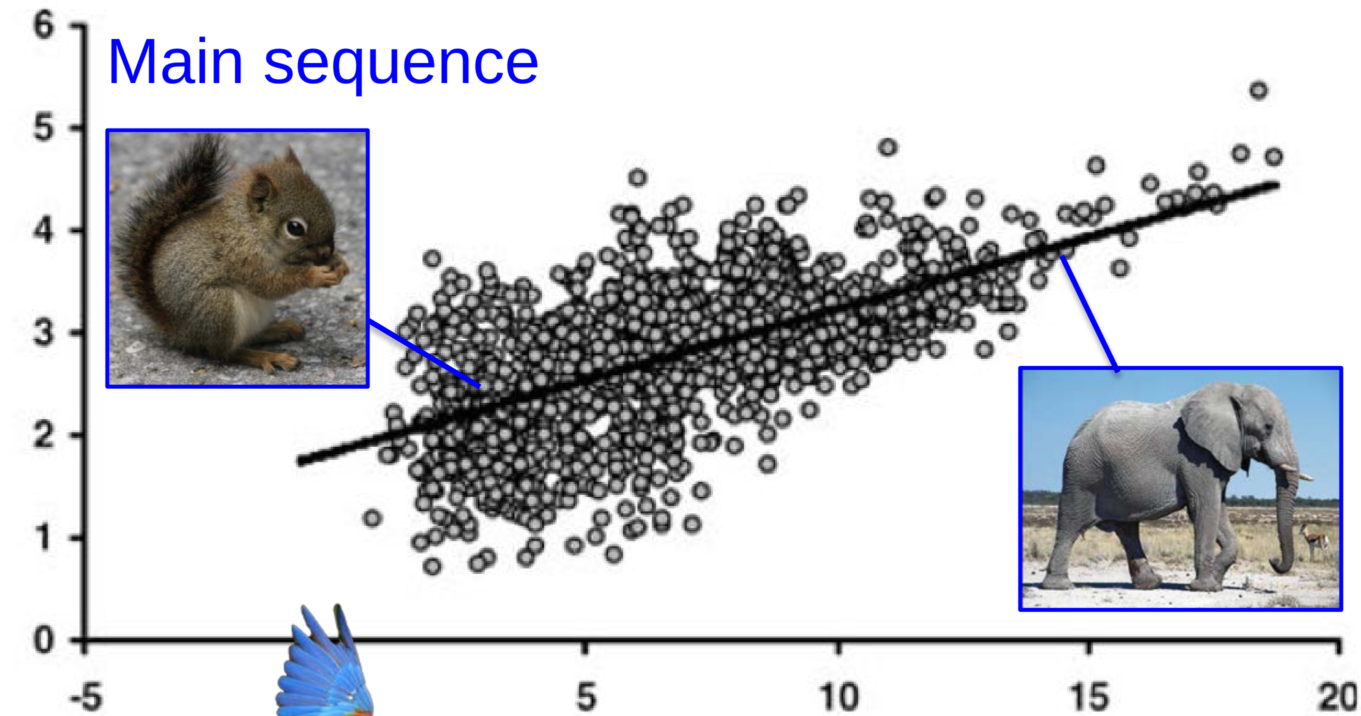


Herschel extends the view on the obscured SFR – M★ main sequence to z=3.5





Schreiber +2014

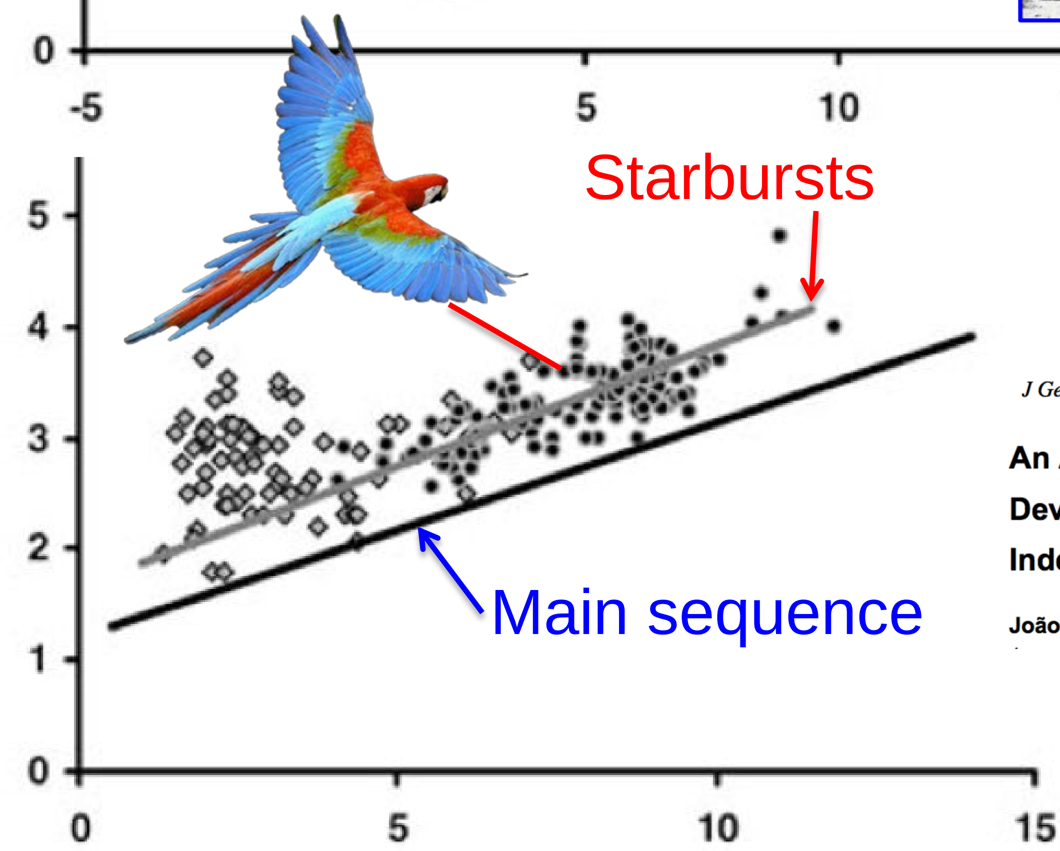


mass

longevity

~1 billion heart beats

heart rate ~ 1/SFR



mass

J Gerontol A Biol Sci Med Sci. 2007 February ; 62(2): 149–160.

An Analysis of the Relationship Between Metabolism, Developmental Schedules, and Longevity Using Phylogenetic Independent Contrasts

João Pedro de Magalhães[1], **Joana Costa**[2], and **George M. Church**[1]

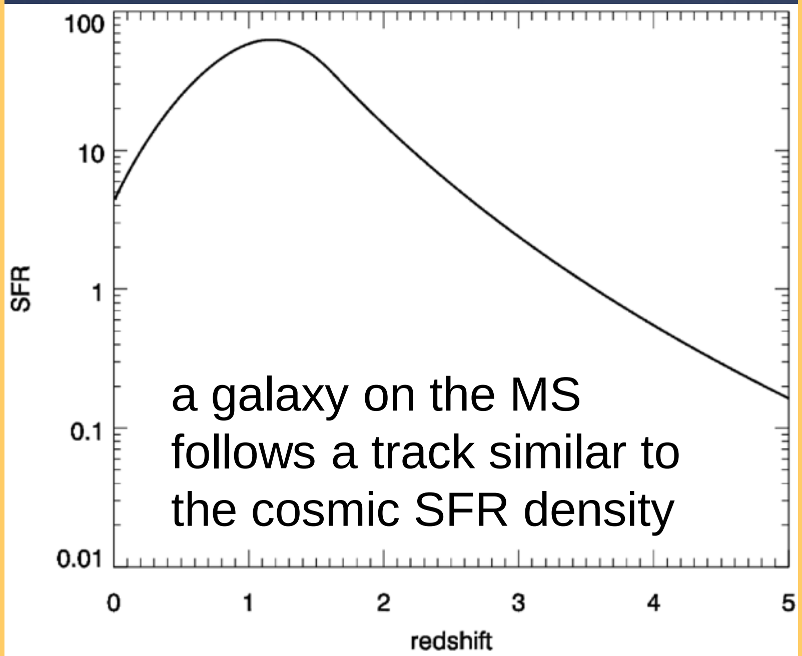
1456 mammals, birds, amphibians, reptiles

Implications of the SFR – $M_\star$ "main sequence" of SF galaxies

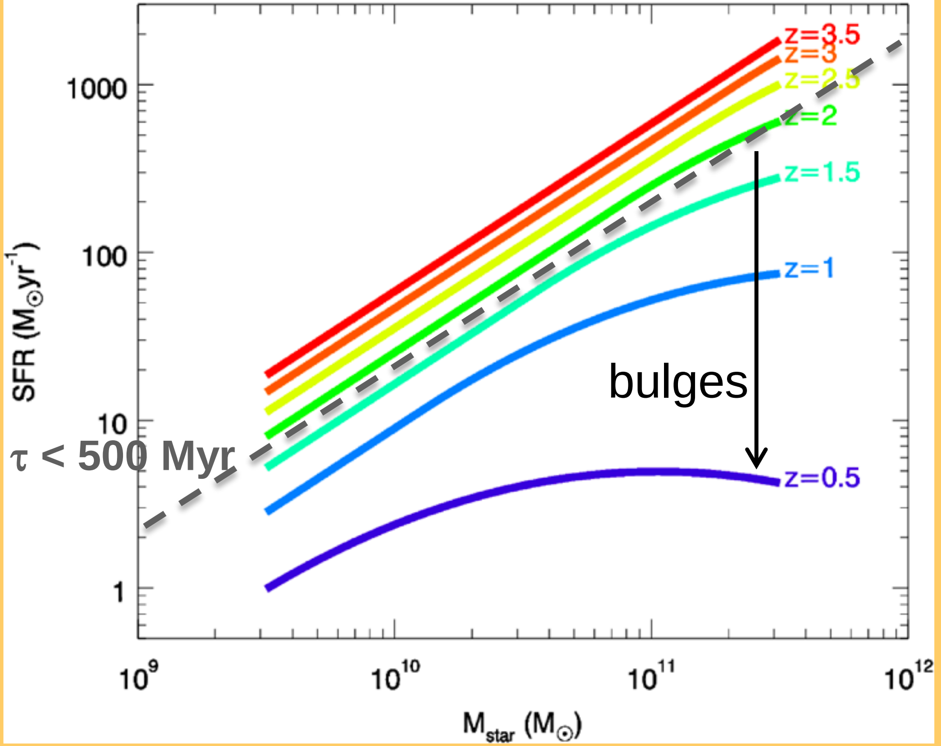
• At any given stellar mass, 68% of the galaxies have the same SFR within a factor 2 (seen by Herschel from at all redshifts between z=0 and 3.5)

• No sign of any variation of the dispersion of the MS with either redshift or stellar mass : issue for feedback processes supposed to be more efficient for low mass galaxies and depending on z (e.g. Hopkins)

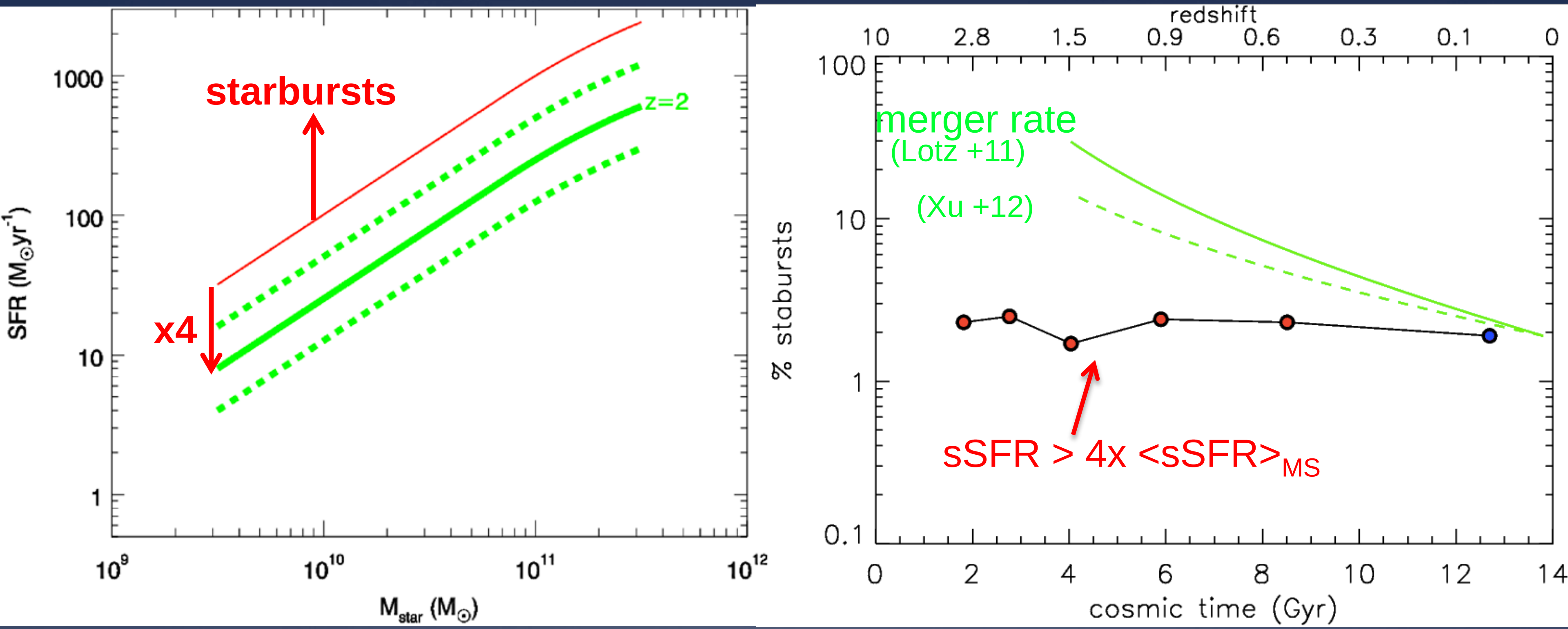
cosmic SFR history (« Madau plot ») does reflect a true universality of star formation of individual galaxies



Consistent with flat universal sSFR=SFR/M*
+ break at low z → bulge formation



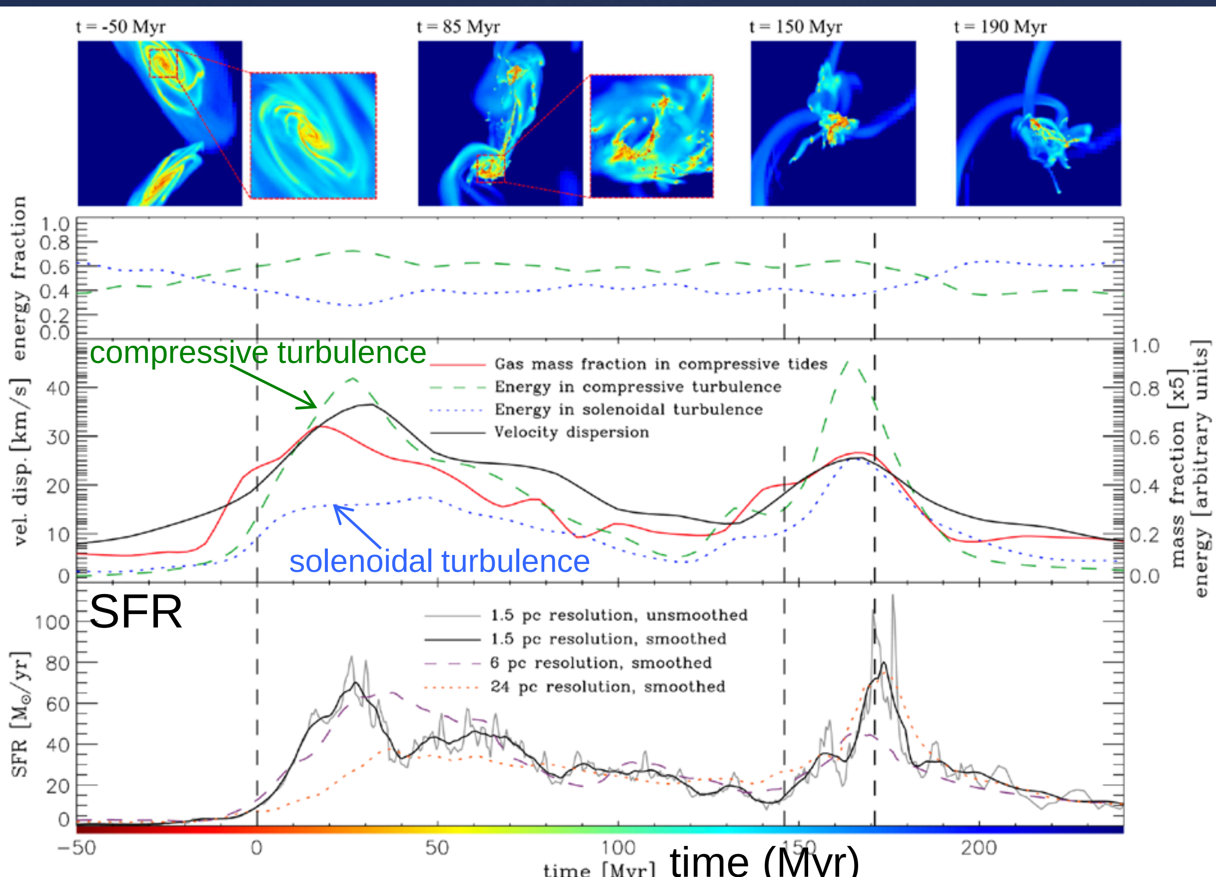
Absence of redshift evolution of the % of starbursts



The fraction of « starbursts » does not evolve over 90% of cosmic time (z=0 to 3.5) (starburst= galaxy with SFR>3-4 x MS)

Merger-driven starbursts in local gas poor galaxies

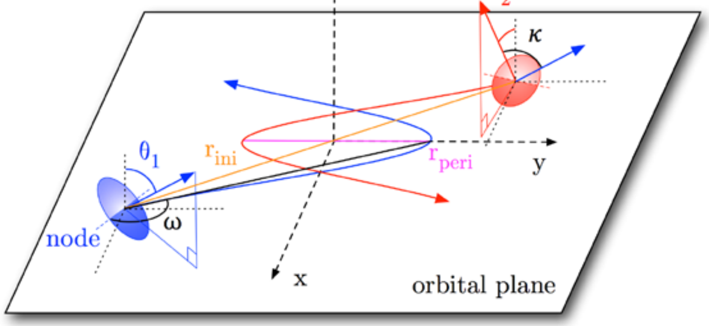
In low gas fraction local galaxies : turbulence ~5 km/s
merger → compressive turbulence → ~50km/s → strong SFR

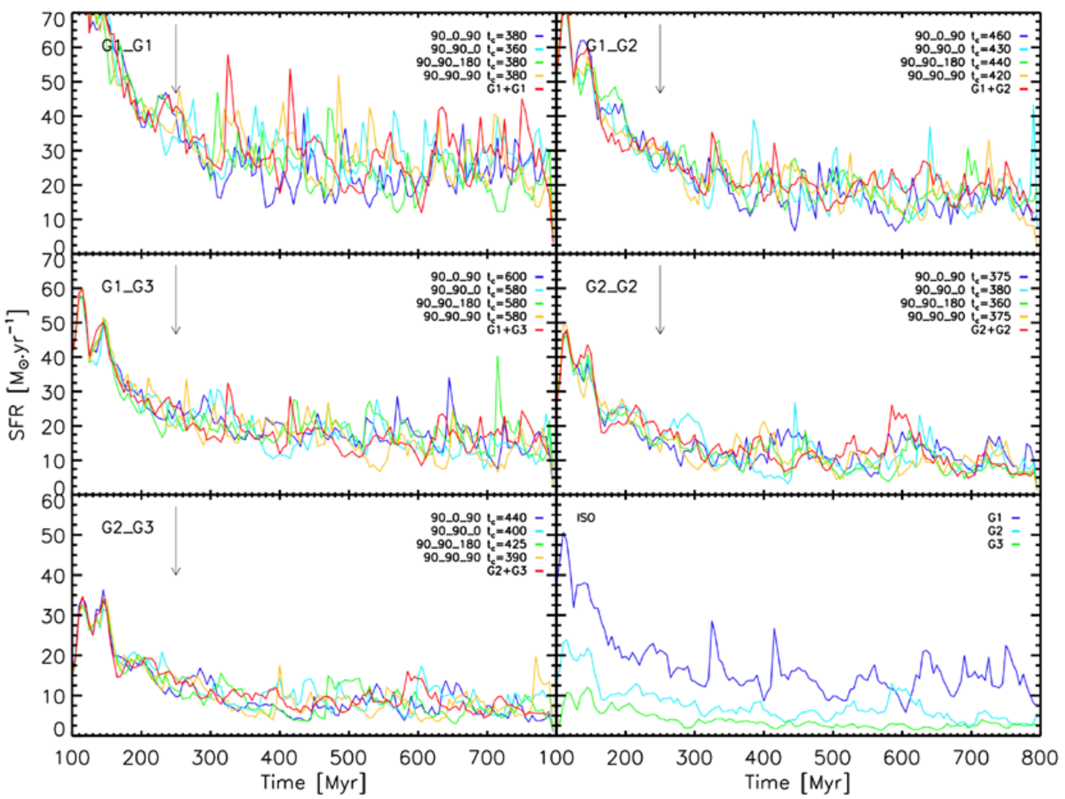


Renaud+2014

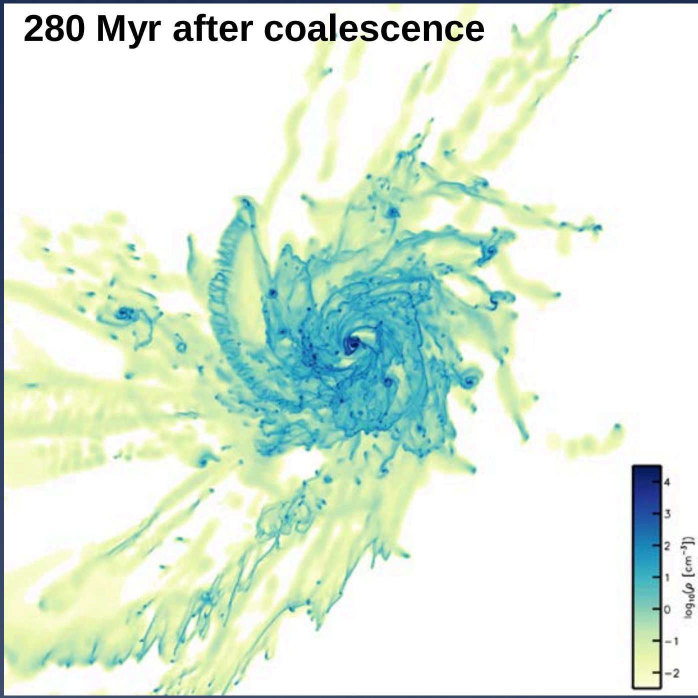
Impact of mergers on gas rich spirals (typ. of z~1-2 galaxies)

merger of 2 gas-rich galaxies (50%) with various impact parameters,…





280 Myr after coalescence



Merging and Isolated high-Redshift Adaptive mesh refinement Galaxies (MIRAGE) Perret et al. 2014

The enigma of star formation in the Milky Way

Interstellar Gas and Star Creation

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(Eingegangen am 29. Juni 1957)

*If no external supply is available, the gaz in the solar vicinity will be exhauted about **700 million years** from now*

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(Diehl *et al*. 2006 Nature)

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Neutral gas (HI): $5 \times 10^9\ M_\odot$

→ **Gas refilled (e.g. infall, return gas fraction) = Van den Bergh (1957)**

→ **SFR reduced with reduced gas content: SFR ~ ρ_{gas} = Schmidt (1959)**

The MS is probably the best evidence for extragalactic infall

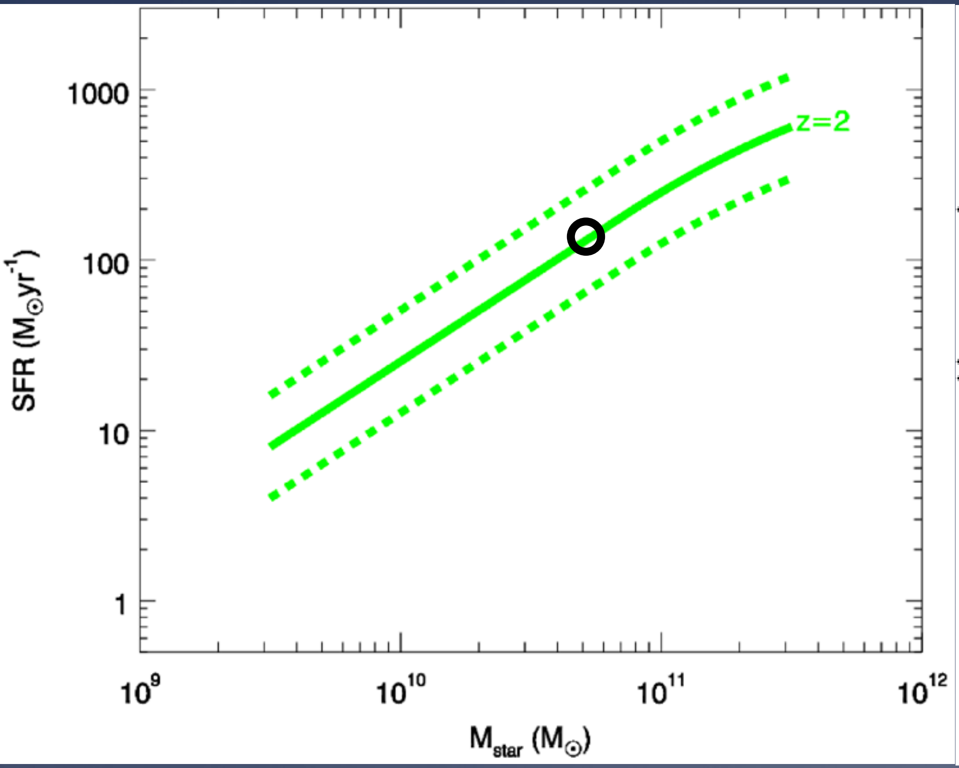
Gas fraction at z~2 : ~50% → $M_\star = 5\times10^{10}\,M_\odot$ = M_{gas}

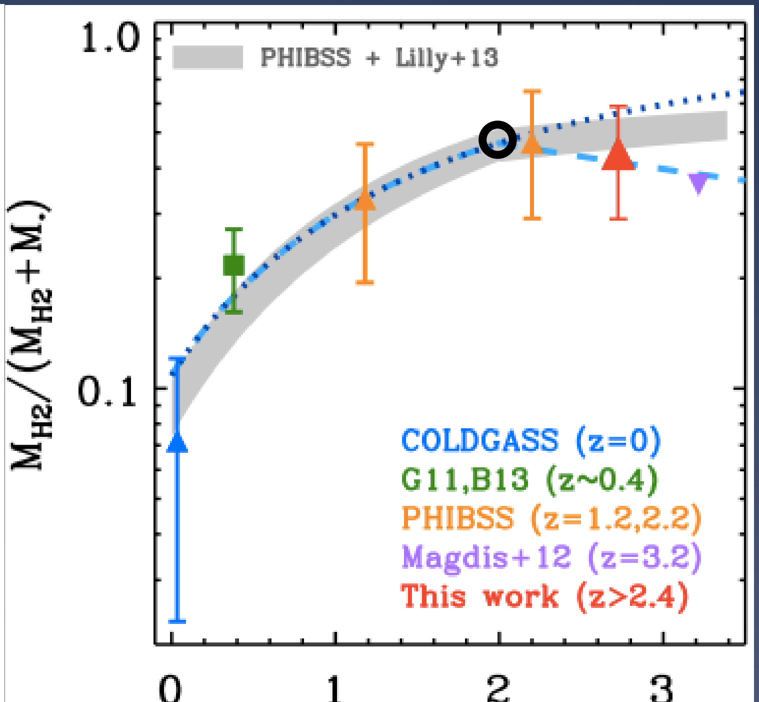
SFR of such galaxy at z~2: ~80$M_\odot yr^{-1}$ → gas exhausted in ~600 Myr

This corresponds to the cosmic time separating z=2.2 and z=1.8 !

Yet, 68% of z=1.8-2.2 galaxies are on the MS…

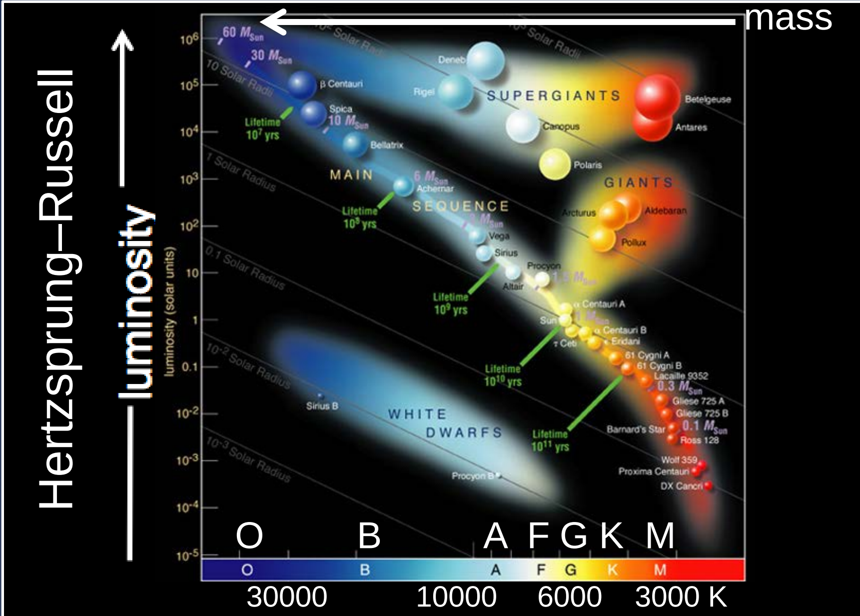
→ need for extra fueling : evidence for infall !

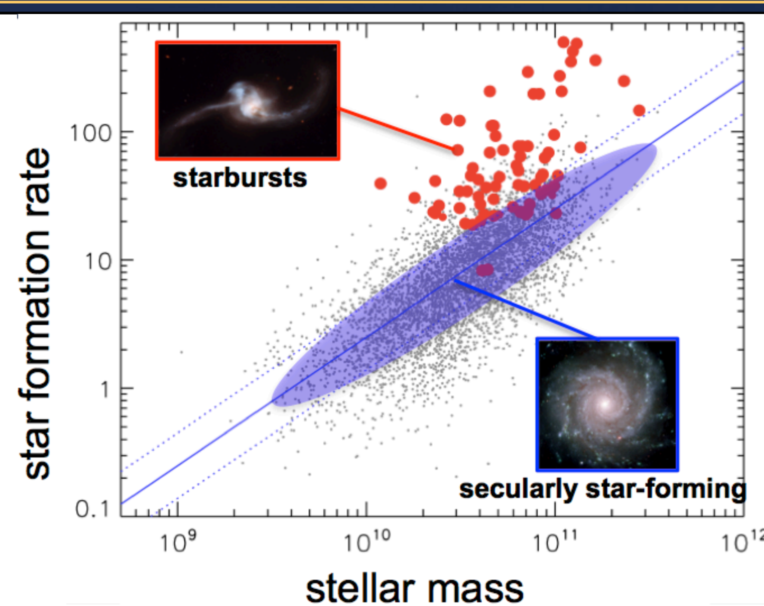




Saintonge +13

Analogy between the stellar and galactic main sequences





Stars spend most of their life on the MS

Massive stars die first

Stars have stellar winds

Stars spend a short fraction of their life in a more luminous phase (giants, AGB)

Universal efficiency of light production : $0.007\ \Delta m\ c^2 \rightarrow$ light

The most massive stars produce black holes that kill them

Dying stars = 10^9 times more luminous

alaxies spend most of their life on the MS

Massive galaxies die first

Galaxies have galactic winds

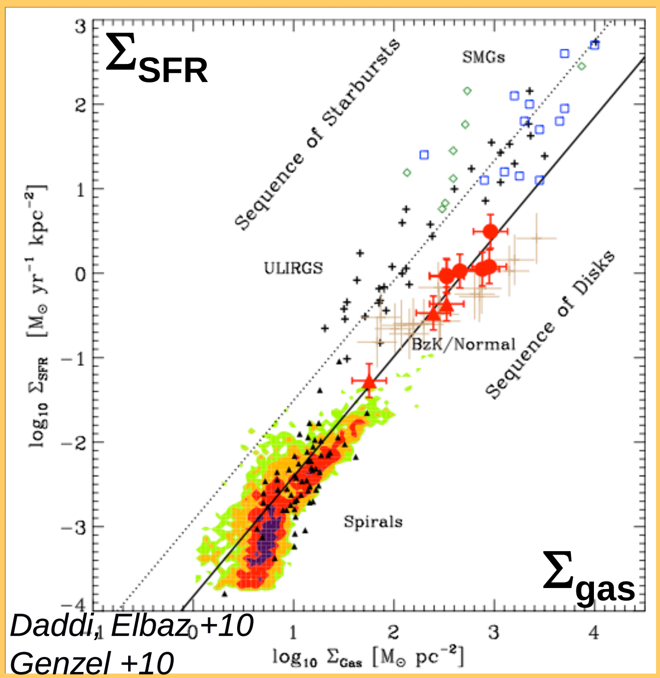
Galaxies spend a short fraction of their life in a more luminous starburst phase

niversal efficiency of light production : FR = $4 \times 10^8\ M_{dense}$

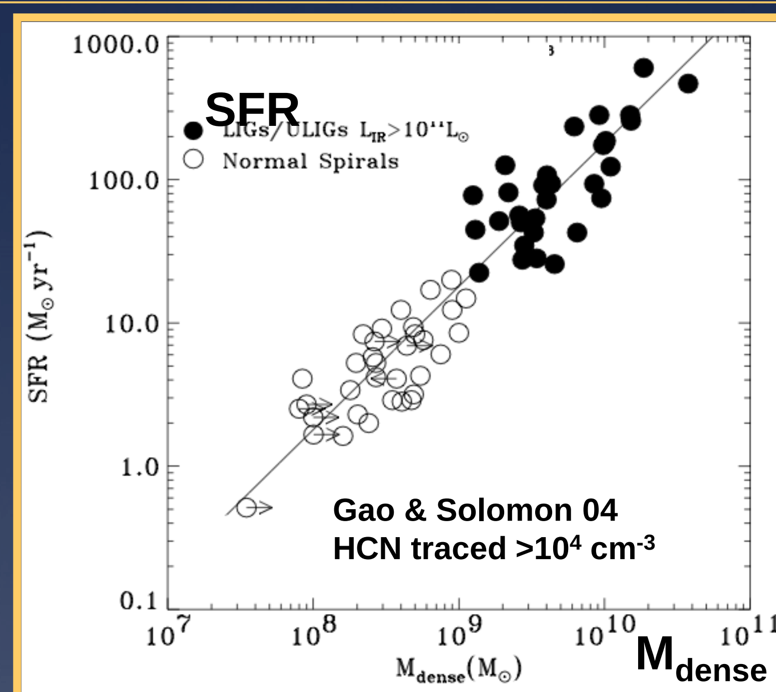
The most massive galaxies produce black holes that kill them (?)

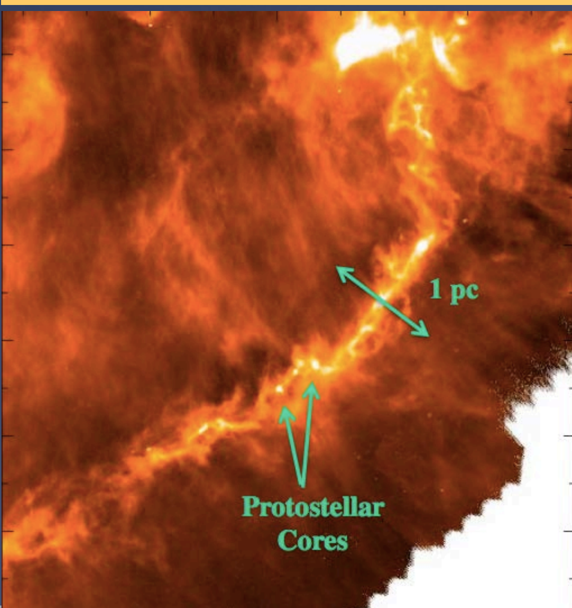
Dying galaxies more luminous ? (starbursts ?)

Self-regulated star-formation by turbulence appears to be the key :
dense gas formation at the end of turbulent cascade drives the SFE



$\alpha_{CO}=M(H_2)/L_{CO}$
α_{CO}=0.8 (z~0 ULIRGs)
α_{CO}=4.5 (z~2 ULIRGs)
& MW





P.Andre (10,13): formation of stars from pre-stellar cores in filaments

1. **Large-scale MHD supersonic 'turbulence' generates filaments**
2. **Gravity fragments the densest filaments into prestellar cores**

SFR = $4.5 \times 10^{-8}\ M_{dense}\ M_{\square}yr^{-1}$

C.Lada (12): SF in molecular clouds in MW

SFR = $4.6 \times 10^{-8}\ M_{dense}\ M_{\square}yr^{-1}$

Gao & Solomon (04): HCN probed dense gas in entire galaxies

SFR= $1.8 \times 10^{-8}\ M_{dense}\ (10/a_{HCN})\ M_{\square}yr^{-1}$

$\alpha_{HCN}=M_{dense}/L_{HCN}$~10 $M_{\odot}$(K km s^{-1} pc^{-2})$^{-1}$

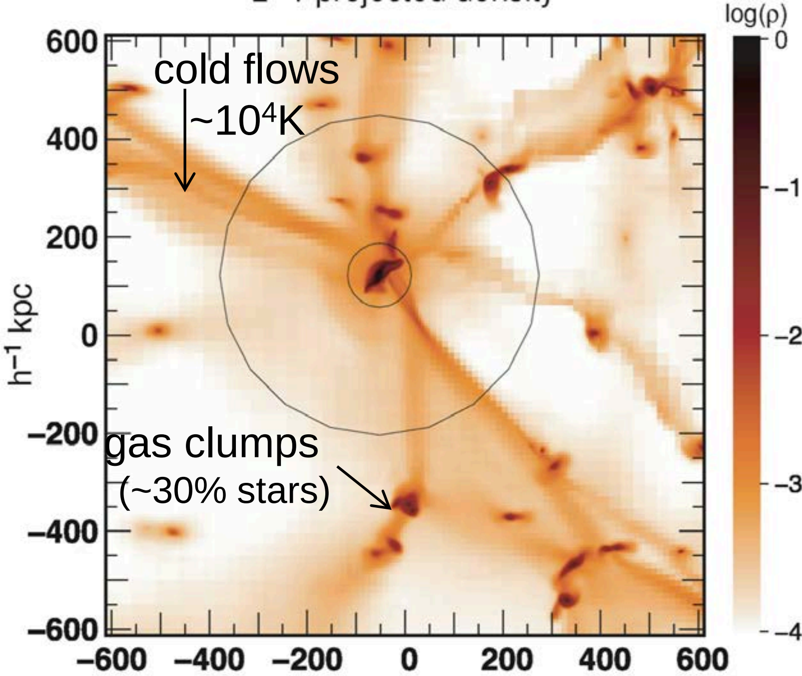
Extragalactic emission Herschel + Planck

MareNostrum simulation (AMR)
71 Mpc, res° 1.4 kpc
Ocvirk, Pichon & Teyssier 2008

Cold streams in early massive hot haloes as the main mode of galaxy formation

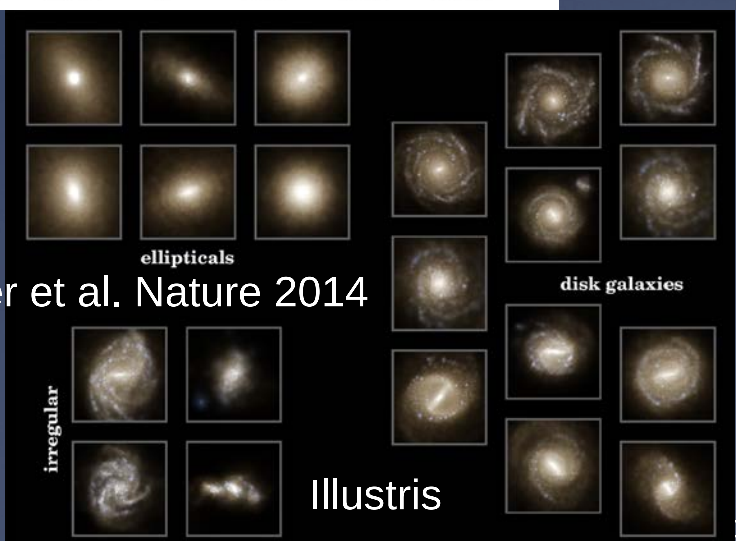
Nature 2009

A. Dekel[1], Y. Birnboim[1,2], G. Engel[1], J. Freundlich[1,3], T. Goerdt[1], M. Mumcuoglu[1], E. Neistein[1,4], C. Pichon[5], R. Teyssier[6,7] & E. Zinger[1]



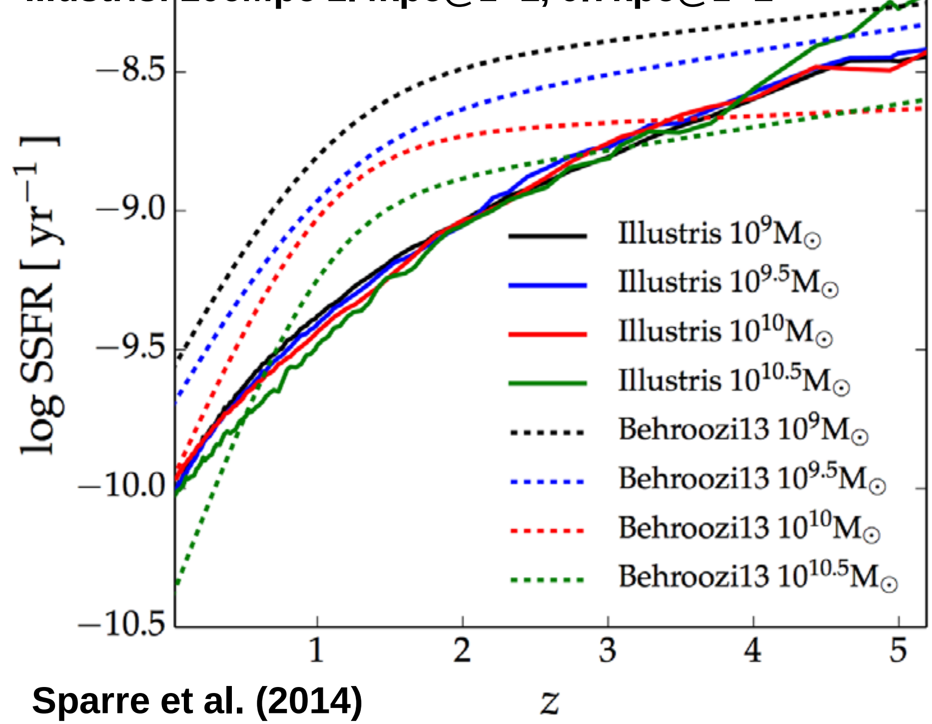
3/4 of star-formation fed by smooth streams = « cold flows »

accretion rate ~ $M_{halo}^{1.15} (1+z)^{2.25}$ x 0.165
where $M_{baryons}/M_{halo}$=0.165



Vogelsberger et al. Nature 2014

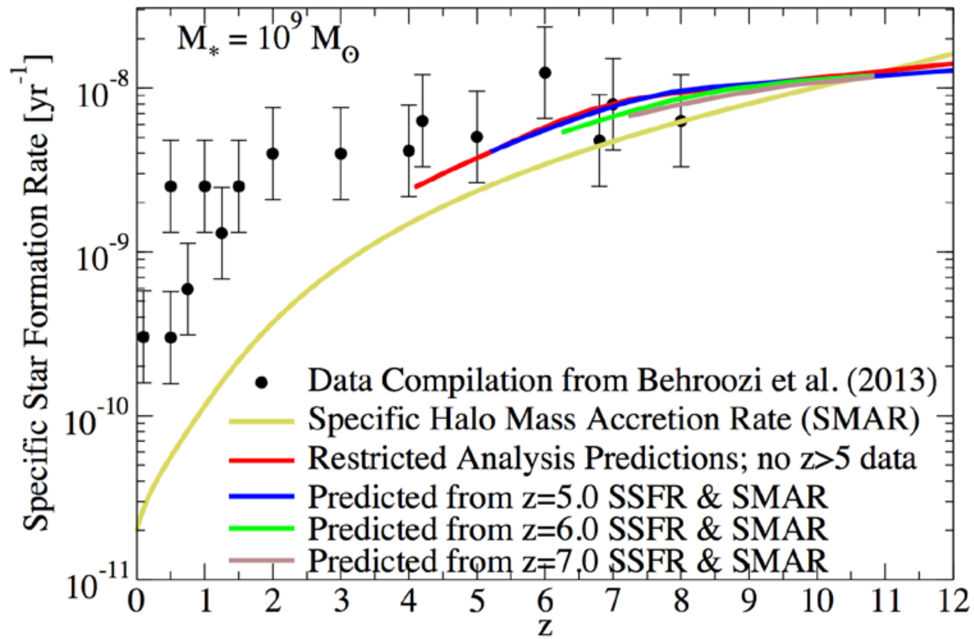
Illustris: 106Mpc 1.4kpc@z>1, 0.7kpc@z<1

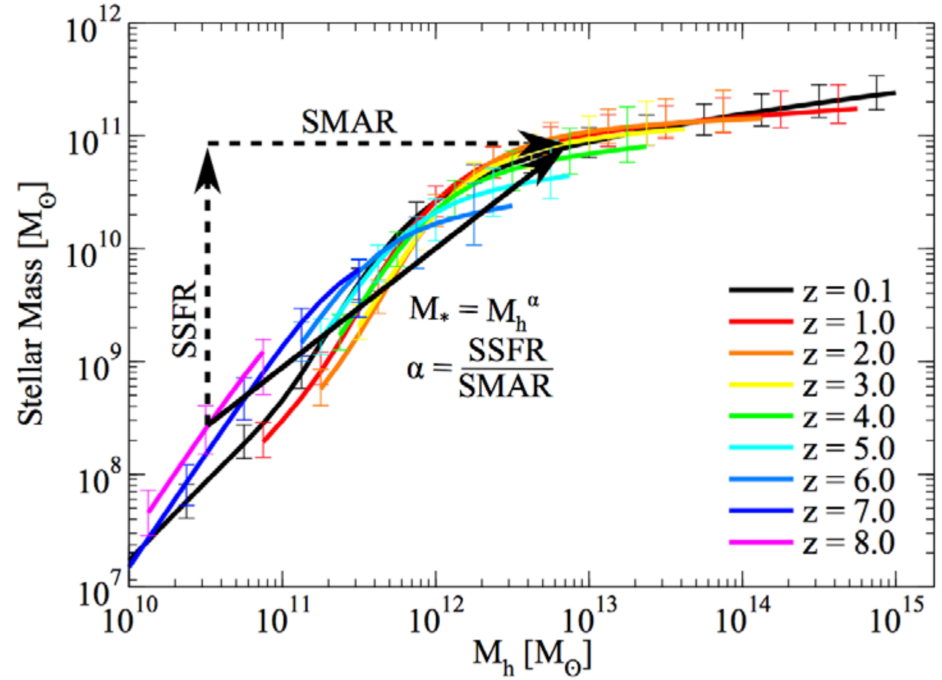


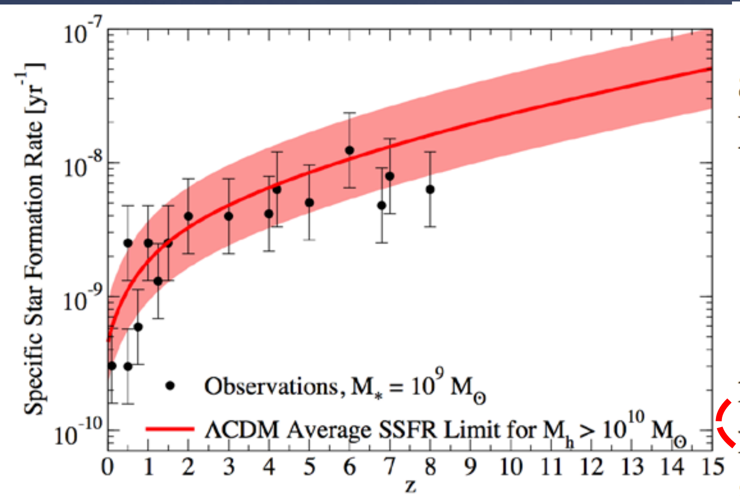
Sparre et al. (2014)

David Elbaz

Tension at z~2 between "main sequence" and models







Behroozi & Silk (2014) :

Typical values of α for $10^{10} M_\odot$ and larger halos range from $\alpha \approx 2$ at $z = 0$ to $\alpha \approx 1$ at $z > 4$. It is difficult to imagine that α could be much higher than 2

mass to the one-third power. That said, we consider values from $\alpha = 1$ to $\alpha = 4$ to cover any exotic future feedback mechanisms.

Conclusions

New era:

we can now bridge the Mpc and pc scales

- Universality of SF :
  - 68% of galaxies have the same SFR with x2 at given M* (SFR – $M_\star$ MS) over at least 90% of the Universe age
  - universal conversion of dense gas into stars
  - Universal IR spectral energy distribution of distant galaxies

→ key role of turbulence to explain self-regulated star formation

We have entered the high precision cosmology era…

…but we still do not understand how galaxies grew through cosmic time

qualitatively expected in the cold accretion paradigm…

…but quantitatively unexpected !

The Universe is globally inefficient in forming stars as compared to DM haloes

yet SF was highly efficient around z~2 for some unknown reason

Can this all be solved by ~~magic~~ (oops sorry) feedback ?